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THE NATURE AND ORIGIN OF THE AMPHIBOLE- ASBESTOS OF SOUTH AFRICA

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I. INTRODUCTION AND ACKNOWLEDGMENTS

Concluding a description of a mineralogical curiosity, a specimen of the blue asbestos from the Cape of Good Hope, Hausmann wrote nearly a century ago: "Should the asbestiform *crokydolite* from

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South Africa be available in greater quantity, then, on account of its property of ready separation into the finest threads of relatively remarkable strength, useful applications . . . might perhaps be found for it" (1831, p. 1597, *trans.*). Today the asbestos deposits of South Africa rival in importance those of Canada and their economic value lies largely in the divisibility and consequent spinning property of the fibre.

Although the results of a number of studies of the South African asbestos have appeared, the chemical and optical data of the asbestiform amphiboles are still scanty and conflicting, and explanations of the origin of the deposits are not yet wholly satisfying. Therefore, at the suggestion of Professor Charles Palache, the writer undertook a study of the extensive amphibole-asbestos collection made under Dr. Palache's direction by the Shaler Memorial Expedition to South Africa in 1922. This collection contains some choice specimens donated by Dr. A. L. Hall and others, and is accompanied by a full range of thin sections.

The work was conducted in the Department of Mineralogy and Petrography of Harvard University, and the writer wishes at once to express his thanks to Dr. Palache for the privilege of studying this valuable material, for outlining the nature of the problem and fruitful lines of attack, and for generous provision of funds for chemical analyses. The writer is also indebted to Professor R. A. Daly for an instructive conversation on the genetic problem, and to Professor E. S. Larsen for some assistance in making optical determinations.

II. THE OCCURRENCE AND DISTRIBUTION OF ASBESTOS IN THE UNION

Although no new field observations are to be offered in this paper, the adequate treatment of the present subject, especially the genetic discussion, demands a brief statement of the geological relations of the asbestos-bearing beds. This will be derived from the comprehensive accounts by Hall (1918 A, B), the recent general text by Du Toit (1926), and the new geological map of the Union by the Geological Survey of South Africa (1925).

The useful asbestiform minerals fall into two groups: serpentine-asbestos and amphibole-asbestos. Although varieties of the former group still constitute the major share of the world's output of asbestos, amphibole varieties are gaining in importance. In South

Africa both types of asbestos are represented; but the deposits of asbestiform serpentine are small compared with the enormous reserves of fibrous amphibole, blue crocidolite, and recently to an increasing extent ash-gray amosite. The present study is concerned only with the amphibole-asbestos.

On the map accompanying Hall's monograph (1918 B, pl. xvi) ten asbestos localities are indicated. Of these the Cape Belt, yielding crocidolite exclusively, is by far the largest. The Lydenburg and Pietersburg Belt in the Transvaal, where both crocidolite and amosite are mined, comes next in size. The remaining regions are relatively small, and with the exception of Zeerust whence amosite is doubtfully reported, they yield only serpentine forms of asbestos.

The Cape Belt stretches northwards from about 25 miles south of Prieska to about 35 miles north of Tsenin in Kuruman, a distance of 240 miles. The width of the belt varies from a maximum of about 30 miles down to about 3 miles. This belt is formed by the outcrop of a series about 3000 feet thick of magnetic jaspers and siliceous ironstones with very subordinate sandstones, limestones and cherts. These beds form the lowest member of the Griquatown Series which in turn represents the uppermost of the three subdivisions of the Transvaal System in Griqualand West.

The Lydenburg and Pietersburg Belt extends west from the neighborhood of Penge to Chuniespoort, a distance of 160 miles, with a mean width of about 10 miles. This belt is formed by a series of ironstones similar to those of the Cape Belt and at the same stratigraphic horizon. As shown in Table I which is drawn from Du Toit (1926, p. 83), both asbestos belts overlie a series of dolomites.

Towards their base the asbestos-bearing ironstones are rather severely folded, especially to the west of the Gamagara Ridge in the Cape Belt. Farther up in the series signs of disturbance decrease and finally vanish. Whereas the Lydenburg and Pietersburg Belt is definitely within the contact aureole of the Bushveld Igneous Complex, no visible igneous body of comparable proportions has affected the Cape Belt.

TABLE I. GEOLOGICAL RELATIONS OF THE ASBESTOS-BEARING IRONSTONES OF SOUTH AFRICA

TRANSVAAL SYSTEM (Pre-Devonian)	TRANSVAAL		GRIQUALAND WEST	
	Pretoria Series	Magaliesberg Group	Griquatown Series	Upper Griquatown beds
		Daaspoort group including the Ongeluk Volcanic Series		Ongeluk Volcanic Group
		Timeball Hill Group (with the Lydenburg and Pietersburg Asbestos Belt near the base)		Lower Griquatown Beds (with the Cape Asbestos Belt)
	Dolomite Series		Campbell Rand Limestones and Dolomites	
	Black Reef Series		Black Reef Series	

III. THE GENERAL CHARACTER OF THE HAND-SPECIMENS

1. THE IRONSTONES

The asbestos seams invariably lie parallel to the bedding in hard, banded ironstones. In color these rock vary from the darkest brown, through brown, purple and red, to ochre, depending on the degree of peroxidation and hydration of the iron content. In 13019¹ from Kliphuis an half-inch band of small pyrites cubes has developed in dense, dark ironstone. The texture grades from finely granular to densely compact. Within the limits of the hand-specimens the bands, which are defined by sharp changes of color rather than of texture, have widths ranging from a mere hair's breadth to one inch or more; bands of the latter width are rare, however. Sometimes the banding of the ironstones shows little or no disturbance; often the bedding is mildly warped together with the asbestos seams. In an exceptional case, such as 13073 from Warrendale near Daniels Kuil, severe contortion is displayed accompanied by a coarsening of grain and a development of siliceous bands.

¹ This and subsequent specimen numbers refer to the catalogue of the Mineral Collection of Harvard University.

2. THE NATURE OF THE ASBESTOS SEAMS

Broadly surveying the hundred specimens constituting the present collection it is clear that the dominant material, apart from the enclosing ironstone, is a blue, fibrous mineral occurring in persistent, concordant, cross-fibre seams. Occasionally, as in 13070 from Koegas and 13072 from Warrendale near Daniels Kuil, the fractured face of the fibrous mass presents a deep-blue, smooth, compact, faintly undulating, silky-lustrous surface, corresponding perhaps to a mass effect of minute unit prism faces of similarly oriented amphibole fibres. In the majority of cases, however, the fractured surface across the seams is lavender blue, non-lustrous and fluffy. In either case bundles of fibres can be readily detached with the fingers and indefinitely disintegrated into threads of unlimited fineness.

Several specimens, such as 13016 and 13017 from Kliphuis and 13047 from Keikamspoor, have bands of acicular brown amphibole arranged in the cross-fibre manner characteristic of the asbestos. The presumption that this acicular amphibole is a morphological variant of the blue fibre is confirmed by later chemical evidence. Thus this coarser material is of particular interest as it permits fuller optical study than can be made with the fine fibres.

Occasionally crystalline structure fails entirely in the blue bands. In 13018 and 13025 from Kliphuis and 13071 from Westerberg the blue bands present a dull, amorphous appearance, and the belief that these bands represent incipient or potential asbestos is again justified by chemical analysis.

In one example, 13067 from Kalkfontein in the Prieska district, the rich blue color is lacking, the seam consisting of greenish gray fibres otherwise similar to the blue fibre. In other specimens, notably 13083 from McBean's Loc and 13092 and 13093 from Penge in the Transvaal, the fibre is silvery, ashy or reddish gray. This is the material for which Hall proposed the name amosite (1918 A, p. 8); and the few specimens in the present collection show that the white fibre tends to much longer development than the blue material, with little loss of flexibility and divisibility.

Some specimens show a transition from the usual blue fibre to a hard, inflexible, golden fibre which can sometimes be crumbled with the fingers with the formation of an ochreous powder; 13033 from Keikamspoor is an example. With increase in the relative

amount of the golden fibre, the seams assume a rich, golden, lustrous fracture-surface whose beauty is enhanced by the variety of reflections resulting from corrugations in the fibres; 13033-13037 and 13039 from Keikamspoort illustrate various phases in the development of this so-called "golden asbestos." With the complete suppression of blue fibre the golden seams assume a still greater hardness and lustre, which, when combined with an undulatory fibrous growth, result in "tiger's eye" with the chatoyant lustre prized by the lapidary; 13066 is a beautiful example of this stone.

3. THE STRUCTURE OF THE ASBESTOS SEAMS

The blue fibre seams vary in width from a small fraction of an inch to two inches. Hall states that the Cape fibre rarely exceeds three inches in length, while fibre three-quarters of an inch in length represent 80 per cent of the output of the Westerberg and Koegas workings in 1917 (1918 B, p. 18). Five-eighths of an inch may therefore be taken as a fair average length of the blue asbestos fibre. Golden asbestos and tiger's eye occur in seams of similar width. In the present collection the white fibre, amosite, reaches a length of nearly 11 inches. According to Hall this is a maximum length for amosite; an output of fibre 4 to 7 inches long can however readily be maintained (1918 B, p. 20).

Although some of the thinner asbestos seams are essentially parallel-sided, some irregularity in width is much more common. A frequent structure is one in which a seam is bounded by one plane contact, the other being undulating or corrugated. Sometimes a seam may be twofold, bounded top and bottom by plane contacts and enclosing a wavy medial band of ironstone, as in 13083 from McBean's Loc. In 13072 from Warrendale, near Daniels Kuil, both contacts of the asbestos seam are undulatory and complementary, the seam being thus divided into pod-like bodies connected by mere filaments.

The cone structure described by Hall is exemplified in 13074 from Kuruman. It results from conical protuberances from the enclosing rock into the asbestos seam, and it is best seen where the specimen has parted along the junction between the asbestos and the wall.

Generally the fibres are oriented normal to the bedding, but occasionally they may assume a notably oblique position. In some

cases the fibres are curved, being nearly normal to one wall and oblique to the other.

IV. OPTICAL AND CHEMICAL STUDY

1. QUARTZ

Quartz occurs in the asbestos-bearing ironstones in three phases which are distinct in grain, in texture and in age. The first mode of occurrence is represented by exceedingly small and indefinite individuals forming the major constituent of the colorless and cloudy bands of the more compact and banded rocks. This is the earliest quartz, evidently representing the almost unaltered siliceous component of the original sediment.

The second type of quartz forms the colorless bands of some of the less cherty and compact ironstones. The individuals are clear, fresh and equigranular, forming interbedded mosaic bands whose granularity averages 0.05 mm. These mosaic bands appear to be the more siliceous bands of the original sediment crystallized under mild metamorphic conditions.

The third quartz phase is clearly the latest. It appears in delicate veinlets of mosaic or fibrous structure sometimes traversing the section with no regard to the bedding direction; sometimes appearing in fine mosaic streaks forming, along with more abundant magnetite, a selvage to the cross-fibre asbestos seams; and sometimes forming massive cross-fibre seams through which is distributed a variable amount of concordant fibrous asbestos. In larger specimens this association results in the "tiger's eye" already described in a previous section. Although it might be held that the fibrous quartz in such specimens has replaced fibrous asbestos, the impression gained from the sections is that the two minerals grew concurrently. It is noteworthy that the quartz fibres in these rocks extinguish under crossed nicols at all angles to their direction of elongation, and that, therefore, they have no tendency to elongate along their principal axes. Precisely the same peculiarity was recently observed by Richards in veins of fibrous quartz and chlorite from Rhode Island (1925). It would thus seem that when quartz either replaces another fibrous mineral or grows concurrently with it, the elongation of the fibres is determined solely by the fortuitous orientation of the first quartz to crystallize, and is independent of the usual prismatic habit of quartz.

2. IRON ORES

Next to quartz, iron ores are the most abundant constituents of the ironstones. The sesquioxide, usually somewhat hydrated, appears to be the earliest and most abundant ore. Magnetite is prominent in many slides and tends to idiomorphism with the appearance of later crystallization.

The ferric oxides are nearly always amorphous. Their color grades from nearly black, through the usual shades of red and brown, to light brown. Often silica and hydrous ferric oxide form a perfectly homogeneous, brown aggregate giving no reaction in polarized light; sometimes ferric oxide is irregularly associated with amorphous magnetite. Rarely ferric oxide occurs in fibres showing pleochroism and parallel extinction. This structure is displayed in sections of the conical protuberances of ironstones which often project from the wall-rock into an asbestos seam. At first sight it might appear that these cones were unaltered relics of ironstone, but their fibrous structure, accurately oriented parallel to the axis of the cone and to the adjoining cross-fibre asbestos, and therefore wholly unlike the unoriented ferric oxide which makes up the unaltered ironstone, clearly indicates a later molecular rearrangement probably contemporaneous with the asbestos formation. Finally ferric oxide occurs in deep-red, translucent patches at the margins of partially reoxidized magnetite grains.

Magnetite is an ever present constituent of the ironstones, and an infallible associate of the asbestos seams. Grains of magnetite show a strong tendency to coalesce into opaque bands which give the banded appearance to the hand-specimens. Euhedral outlines are common and various sections of the octahedron and perhaps the dodecahedron sometimes simulate rhombohedral shapes. Magnetite crystals never have the appearance of detrital grains, and thus it is clear that they must have formed *in situ* by the partial reduction and crystallization of the earlier ferric oxides. Associated with the asbestos seams magnetite may occur in irregular black bands of coalescing grains at the contacts between the asbestos seams and the wall-rock; or it may form undulating bands of discrete grains distributed with some regularity through the asbestos seams; or it may occur as a quite irregular scattering of idiomorphic grains.

In a few rocks magnetite bands appear disposed in a manner which at first sight seems inexplicable. In such rocks the bedding

as defined by magnetite bands at some distance on either side of an asbestos seam, is perfectly flat. In the neighborhood of the seam, however, but still within the wall-rock, the magnetic bands assume a wavy shape in sympathy with the wavy contact of the asbestos seam with the wall-rock. No tectonic influence could reasonably be invoked to produce this selective distortion, and thus one is driven to the conclusion that during the development of the asbestos seams the entire rock in the neighborhood of the plane of alteration acquired a kind of molecular mobility resulting in the regular disposition of the various materials when the change was complete. Although at first sight perhaps somewhat hypothetical, this molecular mobilization of the ironstone around the asbestos seams is precisely what must have happened in the case of the cones of ferric oxide described above. In other words, the structural relations of asbestos seams and magnetite grains indicate that these minerals formed contemporaneously.

A typical fine-grained, barren magnetite-quartzite and a representative sample of the cryptocrystalline ferruginous chert adjoining a crocidolite seam were analyzed with the results given in Table II. In the appended deduced mineral constitutions the monohydrates of alumina and ferric oxide have been formed for the sake of simplicity. Phosphoric and carbonic acids have been combined with magnesia and small proportions of manganous oxide and magnesia are combined in the spinel of I which is, however, still essentially magnetite.

These analyses confirm the optical observations which indicated that the ironstones consist almost wholly of quartz and variously peroxidized and hydrated oxides of iron. The small amount of aluminium hydrate and the minute proportions of carbonates and phosphates indicated chemically are not detected by the microscope. It is significant that neither in the barren ironstone nor in the ironstone immediately adjacent to a crocidolite seam were lime or the alkalis found in determinable amounts. In the degree to which iron is peroxidized and hydrated the two analyses differ widely, in full accord with the microscopic observations. In I, which is largely a fine-grained crystalline mosaic, considerable reduction has taken place giving about 18 per cent of magnetite, while water is present in sufficient amount to give about 22 per cent of monohydrates of the sesquioxides. In II, on the other hand, which is largely an uncrystallized aggregate, iron oxide is entirely

in the ferric state, and there is enough water present to produce 54 per cent of monohydrates of ferric oxide and alumina.

TABLE II. NEW ANALYSES OF IRONSTONES FROM SOUTH AFRICA

	I	II
SiO ₂	45.50	43.85
TiO ₂	trace	trace
Al ₂ O ₃	1.52	1.44
Fe ₂ O ₃	44.16	47.88
FeO	4.63	trace
MnO	0.57	0.00
MgO	0.42	0.35
CaO	trace	trace
Na ₂ O	trace	trace
K ₂ O	trace	trace
H ₂ O+	2.30	5.55
H ₂ O-	0.60	0.35
P ₂ O ₅	0.05	0.06
SO ₄	0.00	0.00
CO ₂	0.12	0.35
S	0.00	0.00
	<hr/> 99.87	<hr/> 99.83
SiO ₂	45.50	43.85
Al ₂ O ₃ · H ₂ O	1.80	1.67
Fe ₂ O ₃ · H ₂ O	20.11	52.33
Fe ₂ O ₃	13.60	0.80
FeO · Fe ₂ O ₃	17.90	0.00
MgO · CO ₂	0.24	0.67
MgO · P ₂ O ₅	0.09	0.10

I.—Banded ironstone, 13001 (fine-grained, barren, magnetite-quartzite), from Prieska Kopje. Analysts, W. H. and F. Herdsman.

II.—Ironstone, 13010 (cryptocrystalline, ferruginous chert adjacent to crocidolite seam), from Kliphuis. Analysts, W. H. and F. Herdsman.

3. CROCIDOLITE

PREVIOUS WORK. Optical and chemical study of the blue, fibrous amphibole-asbestos, the dominant mineral in the collection, yielded a number of additions and contradictions to the existing data of crocidolite; a brief review of previous work is, therefore, desirable.

The Cape crocidolite has been analyzed a number of times and several attempts have been made to establish its chemical constitution. In Table III previous analyses have been arranged in

chronological order together with two analyses of crocidolite from Cumberland, Rhode Island.

The first work was done by Klaproth (1815) who published a short description of a new, non-fibrous, massive, blue mineral collected by Lichtenstein at the Orange River near Prieska in the Cape. Klaproth gave an analysis (I), and proposed the name *Blau-Eisenstein* for the material.

Some years later Hausmann and Stromeyer (1831) described a blue, fibrous mineral from the Cape whose chemical identity with Klaproth's *Blau-Eisenstein* they established by two analyses (II, III). To avoid confusion with the pre-existing term *Blau-Eisenerde* Hausmann suggested the apt name *Krokydolith* for both materials, recommending that the fibrous material be called *asbestartiger Krokydolith* to distinguish it from the massive variety. *Krokydolith* is derived from *κροκίς*, meaning "fluff" or "woof."

Much later Doelter (1880) analyzed the Cape crocidolite (IV) and showed for the first time that the mineral contained abundant

TABLE III. PREVIOUS ANALYSES OF CROCIDOLITE FROM SOUTH AFRICA AND RHODE ISLAND

	I	II	III	IV	V	VI	VII
SiO ₂	50.0	50.81	51.64	52.11	51.89	52.13	51.03
Al ₂ O ₃.....	.....	.....	.....	1.01	.....	.....	.....
Fe ₂ O ₃.....	.....	.....	.....	20.62	19.22	15.93	17.88
FeO.....	40.5	33.88	34.38	16.75	17.53	21.25	21.19
MgO.....	.....	2.32	2.64	1.77	2.43	0.22	0.09
CaO.....	1.5	0.02	0.05	.....	0.40	.....	.....
MnO.....	.....	0.17	0.02	.....	.....	.....	.....
Na ₂ O.....	5.0	7.03	7.11	(6.16)	7.71	6.26	6.41
K ₂ O.....	.....	.....	.....	.....	0.15	.....	.....
H ₂ O.....	3.0	5.58	4.01	1.58	2.36	3.95	3.64
	100.0	99.81	99.85	100.00	101.69	99.74	100.24

I.—Blau-Eisenstein, Cape of Good Hope. Analyst, Klaproth. Ref. Klaproth, 1815.

II, III.—Krokydolith, Cape of Good Hope. Analyst, Stromeyer. Ref. Hausmann and Stromeyer, 1831, p. 1585.

IV.—Krokydolith (Blau-Eisenstein), Cape of Good Hope. Analyst, Doelter. Ref. Doelter, 1880, p. 40.

V.—Krokydolith, Cape of Good Hope. Analyst, Renard. Ref. Renard and Klement, 1884, p. 537. Summation given, 101.71.

VI, VII.—Crocidolite, Beacon Pole Hill, Cumberland, Rhode Island. Analyst, Chester. Ref. Chester and Cairns, 1887, p. 109. Summation of VII given, 99.94.

trivalent iron; lack of sufficient material to permit direct determination of the alkalis, however, renders this analysis somewhat unsatisfactory. Doelter believed that the water of the analysis is unessential, and concluded that crocidolite might be a fibrous form of arfvedsonite.

Soon after this Renard and Klement (1884) made the first attempt to establish the chemical constitution of the Cape crocidolite. Their analysis (V) leads to the formula: $\text{H}_2\text{O} \cdot 2\text{Na}_2\text{O} \cdot 4\text{FeO} \cdot \text{MgO} \cdot 2\text{Fe}_2\text{O}_3 \cdot 14\text{SiO}_2 + \text{H}_2\text{O}$, with tolerable agreement between the found percentages of the oxides and those demanded by the formula. Finding that their analysis gave 15 basic molecules and 14 molecules of silica these authors concluded that one molecule of water was uncombined. As the serious error represented by the high summation might well be concentrated in one of the smaller constituents, the results of these authors cannot be regarded as conclusive. This appears to be the last chemical work to have been done on crocidolite from the Cape.

Shortly after the above work Chester and Cairns (1887) gave an account of crocidolite from Cumberland, Rhode Island. Duplicate analyses (VI, VII) result in another formula: $2\text{H}_2\text{O} \cdot \text{Na}_2\text{O} \cdot 3\text{FeO} \cdot \text{Fe}_2\text{O}_3 \cdot 9\text{SiO}_2$, in which magnesia is neglected as unessential and water is regarded as entirely basic. In spite of the imperfections of the previous analyses of the Cape material it is clear that the mineral from Rhode Island differs somewhat from the Cape crocidolite in that the iron is in a lower state of oxidation, the magnesia is vanishingly small, and water is notably higher.

For crocidolite the sixth edition of Dana's *System* adopts a simplified formula: $\text{Na}_2\text{O} \cdot 2\text{FeO} \cdot \text{Fe}_2\text{O}_3 \cdot 6\text{SiO}_2$, which is accepted by Iddings (1911) and by Larsen (1921); this formula omits both water and magnesia and does not agree well with available analytical data.

In a recent paper Gordon (1927) regards crocidolite as a fibrous form of riebeckite to which he attributes the ideal formula: $\text{R}_2\text{O} \cdot \text{R}_2\text{O}_3 \cdot 4\text{SiO}_2$, where R_2O is chiefly soda with some water, and R_2O_3 is mainly ferric oxide.

Previous chemical work has thus shown that crocidolite is a metasilicate of soda, ferrous oxide and ferric oxide, with some water and magnesia. In detail, however, there is lack of agreement in the available analyses and consequently in the derived molecular constitutions.

Apparently the first published optical data on the Cape crocidolite are contained in a note by Johnson (1910). Assuming that he was dealing with fibres extended parallel to c Johnsen observed deep-blue absorption $\parallel c$ and light gray-blue $\perp c$. From this he inferred that $Y=c$, that X and Z , and therefore the axial plane, are perpendicular to c , and that the mineral is optically positive. This author also gives $2V=56^\circ$ to 90° .

Gordon (1927) gives the following data for crocidolite from Orange River, South Africa: $\beta=1.70$; $\gamma-\alpha=0.005$; $X \wedge c$, low; X (near c), bluish green; Y (near a), bluish gray; $Z (=b)$, bluish gray. This orientation disagrees with that of Johnsen.

The works of reference, including Rosenbusch-Mügge (1926), have all adopted for crocidolite the following data by Lacroix (1890) for material from Templeton, Canada: $\gamma-\alpha=0.025$; optically positive; $X \wedge c=18^\circ$ to 20° ; $2E=95^\circ$. No analysis of this material seems to be available, and it is very probable, as Gordon says, that Lacroix's material "is undoubtedly some other amphibole" (1927, p. 193).

Thus optically as well as chemically there is discordance in the published data of crocidolite, and therefore a full restudy of the type material from South Africa is desirable.

NEW OBSERVATIONS. A sample of the finest blue fibre, 13008, from Kliphuis in the Cape Belt, fairly representing the dominant material in the collection, was studied optically and chemically. Even the finest strands were readily separable into still finer fibres and therefore microscopic observations refer to bundles of fibres in which the optical units are oriented with their c axes only in common. The following were observed: color in ordinary light, lavender; absorption $\parallel c$ indigo, $\perp c$ (presumably the mean of the two specific absorption colors perpendicular to c), pale gray-blue; extinction sensibly parallel to c ; refractive indices between 1.695 and 1.705 with double refraction less than 0.010^2 ; elongation negative, and therefore $c=X$ or Y . The fibrous nature of the material coupled with its deep color and low birefringence made further exact observations impracticable. On many bundles of fibres an apparently good biaxial interference figure was obtained; but this figure was regarded as unreliable being no doubt due to the mineral acting uniaxially in bundles of fibres, and thus giving a flash figure in the plane of the principal axis.

² These and subsequent refractive index measurements were made by the immersion method with a probable error not exceeding plus or minus 0.003.

With the expectation of obtaining fuller optical data, the rarer acicular phase, 13016 from Kliphuis, was studied. The thin section shows elongated tablets, needles and fibres of deep-blue amphibole forming a cross-fibre seam in ironstone of the usual appearance. Late ferruginous alteration films roughly follow basal planes and also planes making 30° with the trace of the perfect prismatic cleavage. A single basal section showed intersecting prismatic cleavages less clearly than is usual in amphiboles. The angle of intersection is 54° . Observations on many cleavage fragments of the tabular amphibole gave the following results: $\alpha=1.698$, $\beta=1.699$, $\gamma=1.706$; X=indigo, Y=yellow, Z=indigo; $X \wedge c=0^\circ$, $Z=b$; whence the birefringence is 0.008, and the elongation is negative. Every attempt to obtain an optical figure failed owing to the strong absorption and weak birefringence of the mineral; and therefore the value of $2V$, which should be small according to the indices, and the orientation could not be checked. Also the extreme closeness of α and β rendered the directions X and Y indistinguishable. The pleochroism scheme and the orientation given are the more probable of two possibilities; X and Y may, however, require to be interchanged.

The non-fibrous, incipient or potential crocidolite, 13023 from Kliphuis, agrees with the two specimens just described in every respect except in the size and shape of the optical units. The blue seam is composed of minute, pleochroic, somewhat rounded units arranged either at random or in a crudely stellate manner. Ferruginous films traverse the seam at right angles to its length imparting a transverse structure.

In TABLE IV the new optical observations on crocidolite have been entered together with other recent data of crocidolite and riebeckite from various localities. It will be seen that the optical constants of the two minerals are impressively concordant, and therefore, in view of their chemical similarity, there can be no doubt that crocidolite is a fibrous form of riebeckite. Considering the data of crocidolite alone it will be seen that $X \wedge c=0^\circ$ in the examples from Kliphuis and Narsarsuk, and that therefore as far as the immersion method shows, crocidolite is orthorhombic. But until measurable crystals are found or synthetically prepared it is preferable to preserve crystallographic unity among the soda-amphiboles and retain crocidolite as a monoclinic mineral in which the extinction angle is zero.

TABLE IV. OPTICAL CONSTANTS OF CROCIDOLITE AND RIEBECKITE

Mineral and locality	α	β	γ	$\gamma - \alpha$	Pleochroism			Orientation	Ref.
					X	Y	Z		
Crocidolite, Khilphuis, S. Africa.	1.698	1.699	1.706	0.008	Indigo*	Yellow*	Indigo	$X \wedge c = 0^\circ$ $Z = b$	New data
Crocidolite, Orange R., S. Africa	1.70	.....	0.005	Bluish green	Bluish gray	Bluish gray	$X \wedge c$ low $Z = b$	Gordon, 1927, p. 204.
Crocidolite, Quincy, Mass.	1.699	.....	0.005	Deep bluish green	Bluish yellow	Bluish gray	X near c $Z = b$	"
Crocidolite, Narsarsuk, Greenland.	1.701	.....	0.005	Methyl blue	Straw yellow	Pale Medici blue	$X \wedge c = 0^\circ$ $Z = b$	"
Riebeckite, Cumberland, R. I.	1.695	.....	0.005	Deep bluish green	Yellow	Greenish gray	$X \wedge c = 5^\circ$ $Z = b$	Gordon, 1927, p. 202.
Riebeckite, Quincy, Mass.	1.701	.....	0.005	Bluish smoky green	Olive brownish yellow	Dark smoky green	$X \wedge c = 5^\circ$ $Z = b$	"
Riebeckite, Narsarsuk, Greenland.	1.701	.....	0.005	Grayish blue	Yellow	Dark gray	$X \wedge c = 5^\circ$ $Z = b$	"

* With possible interchange of X and Y.

Chemical analyses of the three phases of crocidolite described gave the values in TABLE V.

TABLE V. NEW ANALYSES OF CROCIDOLITE FROM SOUTH AFRICA

	I	II	III
SiO ₂	51.94	50.71	50.66
Al ₂ O ₃	0.20	0.00	0.04
Fe ₂ O ₃	18.64	20.45	22.64
FeO.....	19.39	17.41	17.05
MgO.....	1.37	2.28	1.99
CaO.....	0.19	0.15	0.01
Na ₂ O.....	6.07	5.75	5.15
K ₂ O.....	0.04	0.07	0.09
H ₂ O+.....	2.58	2.50	2.62
H ₂ O-.....	0.31	0.96	0.15
	<hr/> 100.73	<hr/> 100.28	<hr/> 100.40

I.—Fine, blue, fibrous crocidolite (13008) from Kliphuis, 8 miles N. of Prieska, Griqualand West. Analyst, H. E. Vassar.

II.—Incipient or potential crocidolite, slightly iron-stained (13023) from the same locality. Analyst, H. E. Vassar.

III.—Acicular crocidolite, slightly iron-stained (13016), from the same locality. Analyst, H. E. Vassar.

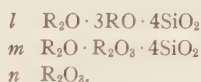
Clearly these three materials, whose optical characters so closely agree, have essentially the same chemical composition. The only noteworthy discordance appears in the values for ferric oxide; but the somewhat higher values for this constituent in II and III are at least partially accounted for by the ferruginous staining in those specimens.

In TABLE VI the same three analyses in the same order have been treated as follows: In each case moisture has been deducted and the remaining oxides have been calculated to 100 per cent. Then the molecular proportions obtained from these figures have been divided by integers chosen to produce approximately constant factors. With exception of the excess of ferric oxide which becomes increasingly larger from I to III, and the slight deficiency of soda in III, the factors show tolerable constancy. As analysis I represents material quite free from visible oxidation we may derive from it the following formula for crocidolite: $\bullet 3\text{H}_2\text{O} \cdot 2\text{Na}_2\text{O} \cdot 6(\text{Fe}, \text{Mg})\text{O} \cdot 2\text{Fe}_2\text{O}_3 \cdot 17\text{SiO}_2$, in which MgO is very subordinate to FeO, H₂O is wholly basic, Fe₂O₃ reacts with its full valency, and SiO₂ is present in sufficient amount to produce an accurately balanced metasilicate.

TABLE VI. MOLECULAR PROPORTIONS FROM THE ANALYSES IN TABLE V.

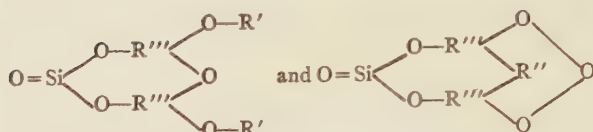
I		II	III
SiO ₂	.862 = 17(.051)	.851 = 17(.050)	.842 = 17(.050)
Al ₂ O ₃	.002	.000	.000
Fe ₂ O ₃	.116 } = 2(.059)	.129 } = 2(.064)	.141 } = 2(.070)
FeO	.269	.244	.236
MgO	.034 } = 6(.051)	.057 } = 6(.051)	.050 } = 6(.048)
CaO	.004	.003	.000
Na ₂ O	.098	.093	.083
K ₂ O	.000 } = 2(.049)	.001 } = 2(.047)	.001 } = 2(.042)
H ₂ O	.143 = 3(.048)	.140 = 3(.047)	.145 = 3(.048)

TABLE VI shows, however, that the found proportions of Fe₂O₃ exceed that required by the formula by amounts which cannot be wholly related to impurity of material and analytical error. This anomaly has frequently been noticed in analyses of amphiboles carrying notable amounts of the sesquioxides; and it is recognized again in Gordon's recently proposed general expression for members of the arfvedsonite-riebeckite group (1927, p.205), which may be written thus:

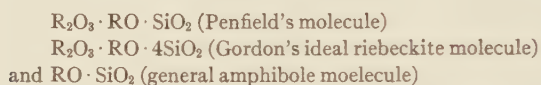


Some authors have attempted to obtain better equivalence between the bases and silica by assuming that H₂O is wholly or partially unconstitutional; but in view of the essential rôle played by the volatiles in the formation of amphibole, and the severe ignition required to liberate combined water, this assumption is unwarranted.

A better explanation is that of Penfield (1907) who concluded that the sesquioxides in amphiboles react with subnormal valency. From the fact that very close equivalence of bases and silica was displayed in a series of careful amphibole analyses when water was included with the bases and the sesquioxides were neglected, Penfield inferred that R₂O₃ combined with hydroxyl, fluorine, the alkalis, lime and magnesia, in that order of preference, to form radicles which require only one molecule of silica to satisfy them, thus:



But the application of this method of interpretation to the present analyses of crocidolite, and to a series of other amphibole analyses to be discussed later, results in an excess of silica. We must therefore conclude that the sesquioxides act partly with subnormal valency in the manner suggested by Penfield, and partly in the normal trivalent manner. Accordingly in TABLE VII the average values of the molecular proportions of the three new crocidolite analyses have been combined to form the following molecules:



where RO embraces $\text{R}''\text{O}$ and $\text{R}_2'\text{O}$. The distribution of R_2O_3 between the first and the second molecules is obtained by the simple equation:

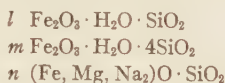
$$T = s + 4(S - s) + R - S$$

where T = total silica, R = total bases including water but excluding the sesquioxides, S = total sesquioxides, and s = sesquioxides in Penfield's molecule.

TABLE VII. INTERPRETATION OF THE AVERAGE OF THE THREE
NEW CROCIDOLITE ANALYSES

	Ratios	$\text{R}_2\text{O}_3 \cdot \text{RO} \cdot \text{SiO}_2$	$\text{R}_2\text{O}_3 \cdot \text{RO} \cdot 4\text{SiO}_2$	$\text{RO} \cdot \text{SiO}_2$
SiO_2	.852	.024	.424	.404
Al_2O_3	.001	} .024	.106	
Fe_2O_3	.129			
FeO	.250			.250
MgO	.047			.047
CaO	.002			.002
Na_2O	.091			.091
K_2O	.001			.001
H_2O	.143	.024	.106	.013

As H_2O fulfils the "RO"-requirements of the first and second terms, and as Al_2O_3 , CaO and K_2O are negligibly small, we may write the constitution of crocidolite as follows:



which neglects the insignificant replacement of a small amount of Na_2 by H_2 in the third term.

In view of the smallness of the coefficient l this method of interpretation may be regarded as unjustified; but it will be shown presently that this term becomes relatively large when the same method is applied to the orthorhombic amphiboles.

4. AMOSITE

PREVIOUS WORK. The name *amosite* was proposed by Hall (1918 A, p. 8) for the long, ash-gray fibre which is abundantly developed in the Lydenburg and Pietersburg Belt in the Transvaal. The term is derived from the initial letters of "Asbestos Mines of South Africa." Hall described amosite as a white, pale-brown, silvery-gray, ash-gray, or very delicately greenish, monoclinic iron-amphibole, which may perhaps form a local variety of crocidolite without the characteristic blue color, or represent a fibrous phase of the cummingtonite—grünerite group of amphiboles. The extinction angle given is from zero to 20° , commonly between 10° and 17° . The following analyses are given by Hall (1918 A, p. 16, and 1918 B, Appendix):

These analyses were evidently made for commercial purposes and much of the material analyzed was evidently not fresh; they indicate that amosite is essentially a ferrous silicate with rather widely varying amounts of alumina, ferric oxide, magnesia, lime, soda and water.

Wherry (1921) examined a specimen of amosite and found that it showed within the limits of error the exact optical properties of ferroanthophyllite; and as Hall's analyses show that amosite is chemically close to grünerite and ferroanthophyllite Wherry concluded that amosite comprises these two species. The description of ferroanthophyllite with which Wherry compared amosite is one by Shannon (1921) of material from Idaho. This mineral has the optical and chemical properties listed under II in TABLES IX and X respectively.

TABLE VIII. PREVIOUS ANALYSES OF AMOSITE FROM THE TRANSVAAL

	I	II	III	IV	V	VI	VII
SiO ₂	49.72	53.34	50.24	49.10	36.20	49.48	47.68
Al ₂ O ₃	5.72	9.35	.....	.....	.....	0.68	trace
Fe ₂ O ₃.....	.....	.....	7.80	.....	12.08	8.16	4.84
FeO.....	37.00	34.35	32.00	43.86	24.27	30.09	36.00
MgO.....	3.77	.74	3.96	6.14	8.50	6.77	6.20
CaO.....	1.65	1.59	trace	0.46	5.56	0.88	trace
Na ₂ O.....	.....	.....	2.12	.....	0.15	0.20	0.28
H ₂ O+.....	2.29	.....	3.00	.....	4.70	2.74	4.50
H ₂ O-.....	.....	0.62	.....	.....	.....	.....	.....
CO ₂.....	.....	.....	.....	.....	8.40	0.56	0.21
	100.15	99.99	99.12	99.56	99.86	99.56	99.71

I, II.—Third-grade, brownish asbestos from near the surface, Penge. Analyst, Hahn.

III.—Best quality "white" asbestos, fourth level, B section, Penge. Analyst, C. Gardthausen.

IV.—Second quality asbestos, Streatham. Analyst, Hahn.

V, VI, VII.—Amosite, Penge. Analysts, Gulick, Henderson & Co.

NEW OBSERVATIONS. The collection contains several large specimens of typical amosite from Penge in the Lydenburg district of the Transvaal. One large mass, 13092, consists of curved, cohering fibres which maintain a length of 4 inches. The coherent mass is pale greenish-yellow in color and somewhat unctuous to the touch. Where the mass has frayed out the fibres are silver-gray and perfectly flexible and divisible. Optical study of small bundles of straight parallel fibres oriented at random with their *c*-axes in common gave the data listed under III in TABLE IX. Chemical analysis of the material yielded the values under III in TABLE X. In addition to the ash-gray fibre just described the collection contains specimens of greenish-gray fibre sufficiently distinct to warrant separate description. This material is represented by a few specimens from Middelwater 10 miles S. of Griquatown, one from Keikamspoort, and one from Kalkfontein in the Prieska district. In hand-specimens the fibre is greenish-gray sometimes stained with iron solutions. The seams are usually less than half an inch wide, and corrugated structure is not developed. In a few cases shearing of the enclosing walls has resulted in oblique orientation of the fibres with respect to the walls. This greenish fibre has the optical and chemical properties under IV in TABLES IX and X respectively.

TABLE IX. OPTICAL CONSTANTS OF AMOSITE AND OTHER ORTHORHOMBIC AMPHIBOLES

Mineral and Locality	α	β	γ	$\gamma - \alpha$	Pleochroism			Orientation	Ref.
					X	Y	Z		
I. Anthophyllite, Franklin, N. C.	1.6288	1.6301	1.6404	0.0116	.....	.....	.....	$X=b$ $Z=c$	Penfield, 1890, p. 396.
II. Ferroanthophyllite, Idaho	1.668	.....	1.685	0.017	Pale brownish green	.....	Deep brownish green	$Z=c$	Shannon, 1921, p. 399.
III. Amosite, Penge Transvaal, 13092.	1.675*	.....	1.702	0.027†	Pale greenish brown	.....	Pale brownish green	$Z=c$	New data
IV. Amosite, Kalkfontein, Cape Province, 13067.	1.663*	.....	1.680	0.017†	Grayish green	.....	Grass green	$Z=c$	New data
V. Gedrite, Fiskernis, Greenland.	1.623	1.636	1.644	0.021	Not appreciable	.....	.....	$X=b$ $Z=c$	Ussing, 1889, p. 609.

$$* \frac{\alpha + \beta}{2}$$

$$† \gamma - \frac{\alpha + \beta}{2}$$

Considering firstly TABLE IX, it will be seen that there is a strong general similarity in the optical properties of anthophyllite, ferroanthophyllite, amosite and gedrite; and that therefore, as far as optics go, amosite belongs properly to the orthorhombic amphiboles. In each case crystallographic *c* is the direction of highest refraction, and where data are given, of strongest absorption. The refractive indices and birefringence of the members of the series vary somewhat evidently in sympathy with chemical composition. Ferroanthophyllite and amosite, which have high iron-contents with correspondingly low magnesia, have systematically higher indices than anthophyllite and gedrite in which iron is very subordinate. From the optical data alone the validity of amosite as a distinct species cannot be judged as even such distinct species as anthophyllite and gedrite would be hardly distinguishable in small fragments.

In TABLE X are listed the analyses of the same five amphiboles. It will be seen that alumina increases progressively from nearly zero in anthophyllite to nearly 22 per cent in gedrite, while silica decreases antipathetically. The divalent bases vary widely and they must clearly be regarded as isomorphous in their relations to the amphibole acid. Ferric oxide varies from zero to about $3\frac{1}{2}$ per cent while water fluctuates between about 1 and 2 per cent. The alkalis are represented only by a small amount of soda in gedrite.

The general molecular relations of the sesquioxides in these analyses are the same as those found and discussed in connection with crocidolite; and therefore the same method of interpretation devised for crocidolite has been applied to the orthorhombic amphiboles (TABLE XI).

TABLE X. NEW ANALYSES OF AMOSITE WITH OTHER ORTHORHOMBIC AMPHIBOLES

	I	II	III	IV	V
SiO ₃	57.98	49.30	47.35	47.04	46.18
TiO ₂.....	.....	.....	trace	trace	.....
Al ₂ O ₃	0.63	1.30	4.20	7.02	21.78
Fe ₂ O ₃.....	.....	2.15	3.34	2.43	0.44
FeO.....	10.39	30.50	36.60	26.10	2.77
MnO.....	0.31	3.48	0.28	0.15	.....
MgO.....	28.69	0.66	5.80	4.96	25.05
CaO.....	0.20	10.73	0.77	10.84	.....
Na ₂ O.....	.....	.....	trace	trace	2.30
K ₂ O.....	.....	.....	trace	trace	.....
H ₂ O+.....	1.67	2.13	1.25	1.05	1.37
H ₂ O-.....	0.12	0.18	0.35	0.45	.....
P ₂ O ₅.....	.....	.....	0.04	trace	.....
S.....	.....	.....	0.05	0.05	.....
SO ₄.....	.....	.....	0.00	0.00	.....
CO ₂.....	.....	.....	trace	0.10	.....
	99.99	100.43	100.03	100.19	99.89

I. Anthophyllite, Franklin, N. C. Analyst, S. L. Penfield. Ref. Penfield, 1890, p. 396.

II. Ferroanthophyllite, Tamarack-Custer Mine, near Gem, Coeur d'Alene district, Idaho. Analyst, E. V. Shannon. Ref. Shannon, 1921, p. 399.

III. Amosite, Penge, Transvaal (13092). Analysts, W. H. and F. Herdsman (new analysis).

IV. Amosite, Kalkfontein, Cape Province (13067). Analysts, W. H. and F. Herdsman (new analysis).

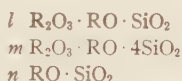
V. Gedrite, Fiskernäs, Greenland. Analyst (?) N. V. Ussing. Ref. Ussing, 1889, p. 609.

TABLE XI. INTERPRETATION OF ANALYSES IN TABLE X

Numbers correspond- ing to Table X		Ratios	$R_2O_3 \cdot RO \cdot$ SiO_2	$R_2O_3 \cdot RO \cdot$ $4SiO_2$	$RO \cdot SiO_2$
I	SiO ₂	.966	.005	.004	.957
	Al ₂ O ₃	.006	.005	.001	
	FeO	.144			.144
	MnO	.004			.004
	MgO	.717			.717
	CaO	.004			.004
	H ₂ O	.093	.005	.001	.087
II	SiO ₂	.822	.019	.028	.775
	Al ₂ O ₃	.013	.019	.007	
	Fe ₂ O ₃	.013			
	FeO	.424			.424
	MnO	.049			.049
	MgO	.017			.017
	CaO	.192			.192
	H ₂ O	.118	.019	.007	.092
III	SiO ₂	.789	.046	.064	.679
	Al ₂ O ₃	.041	.046	.016	
	Fe ₂ O ₃	.021			
	FeO	.508			.508
	MnO	.004			.004
	MgO	.145			.145
	CaO	.014			.014
	H ₂ O	.069	.046	.016	.007
IV	SiO ₂	.784	.070	.056	.658
	Al ₂ O ₃	.069	.070	.014	
	Fe ₂ O ₃	.015			
	FeO	.363			.363
	MnO	.002			.002
	MgO	.124			.124
	CaO	.194	.012	.014	.168
	H ₂ O	.058	.058		
V	SiO ₂	.770	.217		.553
	Al ₂ O ₃	.214	.217		
	Fe ₂ O ₃	.003			
	FeO	.039			.039
	MgO	.626	.104	....	.522
	Na ₂ O	.037	.037		
	H ₂ O	.076	.076		

By allotting three molecules of SiO_2 to each molecule of R_2O_3 it will be seen that a deficit of silica would result, this deficit becoming progressively greater throughout the series, I to V. In the interpretation given, however, a balance between silica and the bases is maintained by introducing the Penfield molecule, $\text{R}_2\text{O}_3 \cdot \text{RO} \cdot \text{SiO}_2$ in appropriate amount. The fact that in gedrite (V) close equivalence is obtained with R_2O_3 combined wholly in the Penfield molecule supports the choice of this combination.

We thus see that the orthorhombic amphiboles, like crocidolite, are expressible as balanced metasilicates in the form:



in which RO again includes R_2O . In anthophyllite (I) l and m almost vanish, and as RO in the third term is mainly MgO , the accepted formula, $\text{MgO} \cdot \text{SiO}_2$, results. In gedrite (V) m vanishes and the formula, $l \text{ Al}_2\text{O}_3 \cdot (\text{H}_2, \text{Na}_2, \text{Mg})\text{O} \cdot \text{SiO}_2 : n (\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$, is obtained. In ferroanthophyllite (II) and amosite (III, IV) the terms l and m are both present in notable amounts, and ferric oxide becomes conspicuous in R_2O_3 . It will also be seen that in II and III, H_2O is sufficient to satisfy the "RO" requirements of the first two terms; in IV, however, a small proportion of lime requires to be introduced.

Amosite evidently belongs to the orthorhombic amphiboles; but on account of the intermediate amount of sesquioxides carried by this mineral, and the fact that these constituents apparently link themselves partly in the subvalent gedrite manner and partly with full valency, amosite cannot be properly identified either with anthophyllite, ferroanthophyllite or gedrite. And therefore, if we are justified in retaining crocidolite, which differs from riebeckite only in its fibrous structure, then there are even better grounds for retaining amosite as a mineral species.

V. GENETIC DISCUSSION

1. THE ORIGIN OF THE IRONSTONES

An attempt to solve the problem of the origin of the asbestos deposits involves a consideration of several distinct groups of evidence; and therefore it seems desirable to discuss these groups in a selected order, progressively bringing the various conclusions

reached to bear on the ensuing considerations. Previous explanations have usually emphasized chiefly one or another of the several aspects of the problem which seem to demand consideration; therefore, in preference to first reviewing these explanations, published opinions on the various points will be referred to in their appropriate connections.

In South Africa massive ironstone formations occur in the Swaziland System, in the Witwatersrand System, in the Transvaal System, and to a very limited extent in the Karoo (Maufe, 1920, pp. 20, 21). In other parts of the world, notably in the Lake Superior region, somewhat similar ironstone formations are known; these always occur in the oldest geological systems. It is now generally agreed that these ironstone formations are of aqueous origin, and furthermore that they originated, not as accumulations of detrital material, but as chemical precipitates. The complete absence of recognizable detrital grains in the many thin sections examined, and the uniquely simple chemical composition of the ironstones revealed by the new analyses both point to the same conclusion. It is true that a fine, compacted, argillaceous sediment is probably microscopically indistinguishable from an indurated chemical precipitate of the same composition; but from the fact that the ironstones contain only $1\frac{1}{2}$ per cent. of alumina we may conclude, not only that these rocks do not represent argillaceous sediments, but that the accumulation of silica and iron oxides, constituting together with water more than 97 per cent of the ironstones, took place outside the range of mechanical sedimentation and therefore remote from land. It might be thought that the ironstones represent ancient deep-sea deposits similar to the red clay now slowly accumulating in the deepest parts of the oceans; but red clay is composed essentially of finely divided, profoundly altered basic eruptive material including many vitreous and crystalline fragments and possessing a chemical composition much too complex to permit comparison with the ironstones. The ironstone formations of the Transvaal System carry occasional intercalations of detrital sediments; and therefore, while it is believed that the ironstones themselves are wholly of chemical origin, it is clear that occasionally the basin of accumulation became sufficiently shallow and restricted to permit mechanical sedimentation.

The origin of the ironstones of various parts of the Union has been briefly discussed by Rogers (1906, pp. 32-33), Maufe (1920,

pp. 20-21), and Wagner (1921, p. 120). Emphasis is usually laid on the similarity of the South African ironstones and those of the Lake Superior region; and the explanations offered are clearly influenced by the conclusions reached by Van Hise and Leith in their exhaustive study of the genesis of the North American occurrences (1911, pp. 499-561). In briefest terms the hypothesis of Van Hise and Leith is as follows: soluble iron salts, supplied either directly by migrating solutions from contemporaneous basic eruptives, or produced by the action of sea-water or meteoric water on basaltic lavas either hot or cold, accumulated in the ocean. These salts were then precipitated in the ferrous condition mainly as carbonate (siderite) and as hydrous silicate (greenalite), some of which is still represented as siderite chert and greenalite rock, while some suffered further chemical changes.

While the South African ironstones are apparently to be explained as chemical deposits the direct application of the hypothesis of Van Hise and Leith is not feasible. Firstly, while the Lake Superior ironstones are directly associated with abundant contemporaneous basic eruptives often having the appearance of submarine extrusives, the South African ironstones, which rest on a formation of limestones and dolomites, carry only an intercalated series of volcanics lying above the main asbestos-bearing horizon. The several methods whereby iron salts are contributed to the sea-water on the Van Hise and Leith hypothesis are thus not directly applicable.

Again, descriptions of South African ironstones contain no compelling evidence of a previous ferrous condition of the iron minerals; and the material studied in the present paper shows no vestige of earlier siderite or greenalite. In the ferruginous cherts of the Lower Griquatown Series Rogers describes rhomboidal areas up to $1/50$ of an inch long composed of chert, brown iron oxide and magnetite in various proportions (1906, pp. 32-33). The inference that these areas are replaced siderite is not beyond question. In the same rocks the present writer has observed polygonal microstructures some of which are rhomboidal in shape; with strong magnification and illumination, however, these structures prove to be due to minute, interlacing needles of iron ores crystallizing from the amorphous ferruginous chert. Also the rhomboidal shapes seen by Wagner in grains of iron minerals in the ironstones of the Rustenburg district (1921, p. 120) might be

random sections of crystalline forms proper to the ores, and not relics of earlier carbonates. Greenalite has apparently never been observed in ironstones from South Africa. The view that these rocks are altered deposits of siderite and greenalite is thus apparently based more on analogy with the Lake Superior deposits than on convincing petrographic evidence. Without denying the possibility of complete obliteration of a previous carbonate condition, if a reasonably probable chemical process can be devised whereby deposits of ferric hydrate and silica could be formed, such a theory would accord more closely with the known petrographic facts.

And finally, Van Hise and Leith are not specific as to the nature of the acid radicle combined in the salts contributed to the sea. To be satisfying a theory involving the introduction of iron salts to the sea-water should specify the acid employed and give reasonable grounds for the choice.

Some assistance in removing these difficulties and thus arriving at a working hypothesis involving the only admissible kind of process, namely a chemical one acting remote from land, may perhaps be gained from a brief consideration of what may be a kindred problem, the origin of the vast body of chlorides in sea-water. In the main, marine chlorides may be regarded either as having condensed from a primitive atmosphere, or as having been "sweated out" of the body of the earth during the consolidation of the crust. Just as a quantitative consideration of the amount of water released during the consolidation of igneous rocks makes it perfectly permissible to relate at least a great bulk of the waters of the hydrosphere to a juvenile source, so a consideration of the amount of chlorine in igneous rocks and volcanic emanations forms the basis of a strong argument for the view that combined marine chlorine is juvenile in origin. Many modern volcanoes and fumaroles, especially the hottest ones as Suess has pointed out (1902, p. 520), emit abundant chlorine, hydrochloric acid and chlorides.³ Becker has calculated that 1000 vents each $6\frac{1}{2}$ centimeters in diameter continuously delivering hydrochloric acid vapor at 200° and 6.62 kilograms per square centimeter into atmosphere

³ Becker's statement, that the most probable origin of the chlorine of volcanoes and deep springs lies in the possible product of decomposition of lawrencite in deeply buried siderolites (1910, pp. 8, 9) seems more difficult to accept than the simple reasonable assumption that chlorine, like water-vapor, is more abundant in igneous magmas than in igneous rocks, and is therefore partially released during the consolidation of igneous rocks.

at 0° would suffice to saturate all river-borne sodium (1910, p. 8). Such a supply of chlorine would surely not be difficult to realize, and therefore, without delaying further with this question which is beside the main issue, we may adopt the already widely held view that marine fixed chlorine was emitted from the body of the earth, and conversely, that the amount of this chlorine gives a rough measure of the amount emitted by volcanoes and fumaroles both subaerial and submarine.

At ordinary temperatures and pressures hydrochloric acid has little action on most silicates; but at 400° and the corresponding pressure dilute hydrochloric acid will convert rock silicates completely into chlorides.⁴ Submarine volcanoes certainly exist and therefore submarine fumarolic action undoubtedly also takes place. To be expelled submarine fumarole vapors must be at a higher pressure than that defined by the overlying column of water; and at some depth in the crust below the sea floor the vapors would probably be at temperatures of several hundred degrees. Water vapor charged with hydrochloric acid, commonly observed in the gases of fumaroles, would therefore cause extensive decomposition of the walls of the fissures traversed by submarine fumarolic and volcanic vapors. Chlorides of all the common bases, iron, alumina, lime, magnesia and the alkalis would thus be formed with concurrent liberation of silica, and the periodic nature characteristic of volcanic and fumarolic action would ensure the transference of these chlorides to the sea-water. On account of the readiness with which ferrous solutions peroxidize to the ferric condition in presence of oxygen, and the fact that sea-water is known to contain notable amounts of dissolved air even at great depths, the iron chlorides formed in the manner suggested would undoubtedly be rapidly converted mainly to ferric chloride.

If the emission of an alkaline reagent be now postulated the desired effect of selective precipitation of iron and alumina as hydrates would be effected; the sea-water would become essentially neutralized as it is now; lime and magnesia would remain in solution to be precipitated later most likely as carbonate and phosphate; and alkaline chlorides would persist in solution as at present. Ammoniacal vapors known to be emitted from some volcanoes and to react with hydrochloric acid vapor to produce clouds of am-

⁴ The success of the Jannasch method of decomposing rocks for analysis depends on this fact.

monium chloride, and soluble alkaline silicates formed in the manner proposed by Van Hise and Leith, suggest themselves as possible available alkaline reagents. In this way silica, ferric hydrate with some aluminum hydrate according to the amount taken into solution by the acidic vapors, would be precipitated almost free from other constituents. With subsequent upheaval of the basin of accumulation this heterogeneous precipitate would become largely dehydrated and indurated to give a rock corresponding substantially to a ferruginous chert.

A full discussion of the origin of the ironstones is outside the scope of the present paper; and therefore the many questions and difficulties attending the admittedly speculative hypothesis offered must be left undiscussed. In view of the relatively slight attention which the genetic problem of the South African ironstones has received even a sketch treatment may be of some value in possibly affording a clue to the true mechanism whereby rocks of such unique chemical and petrographic character may have been formed.

2. THE ORIGIN OF THE CONSTITUENTS OF THE ASBESTOS SEAM

The asbestos seams were manifestly formed after the deposition of the ferruginous cherts in which they occur; and thus the chemical components of crocidolite and amosite may be accounted for in one of the following three ways: (1) by deposition of entirely foreign material from travelling solutions; (2) by reaction of the ferruginous cherts with travelling solutions carrying some component part of crocidolite or amosite; or (3) by molecular reorganization *in situ* of pre-existing materials entirely without introduction of foreign matter.

The first of these modes of origin has apparently never been seriously advocated, although it is virtually implied by Taber's general theory of vein formation, to be considered later. In view of the strong general chemical similarity existing between the asbestos seams and the enclosing ironstones; the fact that occurrences of iron-asbestos are rigorously restricted to ferruginous sediments, just as serpentine asbestos occurs only in ultra-basic igneous rocks of similar composition; and the entire absence of transgressive relations between the asbestos seams and the bedding of the ironstones; a theory of origin involving the introduction of wholly foreign material either in open spaces or by injection along planes of weakness is in the highest degree improbable.

Considering crocidolite first, it will be recalled that this mineral consists essentially of silica, ferric oxide, ferrous oxide, soda and water in descending order of abundance, with magnesia in small amount and alumina, lime and potash in negligible proportions. The ironstones consist of silica, ferric oxide, ferrous oxide and water, with small amounts of alumina and magnesia, and negligible proportions of the other constituents, including soda. The main constituents, silica and iron oxides, are common to both, and the petrographic evidence favors the obvious conclusion that the silica and the iron oxides of the crocidolite seams represent components of the ironstones reorganized *in situ*. This is also the view advocated by Hall (1918 B, p. 125).

Magnesia in crocidolite is about four times as abundant as in the ironstones. Hall suggests that this constituent was derived from solutions ascending from the dolomite formation which underlies the ironstones (1918 B, p. 120); and this view is supported by the rather consistent restriction of crocidolite seams to the lower horizons of the ironstone formation. At the same time the postulate of rising solutions transgressing the bedding offers some difficulties; and since a simple concentration of the magnesia in belts four times as wide as the respective crocidolite seams would be adequate—and the ironstones in the neighborhood of the asbestos seams commonly exhibit a leached appearance—the writer is inclined to explain magnesia in crocidolite to local concentration, and to refer the greater abundance of crocidolite seams in the lower reaches of the ironstone formation to the higher temperatures which probably obtained at the lower horizons.

To explain the presence of about 6 per cent. of soda in the crocidolite seams is perhaps the most difficult part of the genetic problem. Throughout the investigation this question was constantly kept in mind, but no really positive evidence was obtained. Again there are three possibilities: soda may have been a foreign constituent introduced by travelling solutions; or the crocidolite may occupy the place of pre-existing soda-rich bands; or soda may have been uniformly distributed throughout the ironstones and subsequently concentrated in certain bands. The fact that the two ironstone analyses show that these rocks now carry only traces of alkalis is compatible with each hypothesis and therefore does not assist in a decision. In this connection, perhaps the most significant features of the crocidolite seams are their sharp demarcation as

relatively thin planes of great lateral extension, and their constant concordant relation to the bedding of the ironstones. If soda were concentrated by a comprehensive leaching of the ironstones pre-supposed to have contained sufficient evenly distributed soda, it seems very unlikely that these features would be developed in the resulting crocidolite seams; and therefore we may regard this hypothesis as the least probable of the three. Hall inclines to the postulate of pre-existing soda-rich bands (1918 B, p. 120), and suggests that these may be related to deposition in brakish water. Du Toit adopts a similar view (1929, p. 107) and mentions submarine zeolite formation as a possible mechanism for effecting concentration of soda along certain bedding planes. As the ironstones were probably laid down mainly beyond the zone of mechanical sedimentation Hall's suggestion, implying crystallization and occlusion of soda salts in shallow water, does not seem to be supported; and similarly Du Toit's proposal is frankly hypothetical and lacks petrographic corroboration.

The view that soda was introduced by hydrothermal solutions derived from some igneous mass was proposed by Lambert in an unpublished study of the present material. While it is conceivable that injected solutions would invariably follow the bedding of the ironstones, late veinlets of quartz and calcite are frequently found transgressing, and it is probable that alkali-bearing solutions and the consequent crocidolite seams would do likewise if soda were introduced by hydrothermal solutions. Again, Hall (1918 B, p. 120) and Du Toit (1926, p. 107) agree that an adequate igneous source is not known in the Cape Province; and in any case, in the Transvaal where asbestos is developed definitely within the contact aureole of the Bushveldt Intrusion, alkali-free amosite of great fibre-length is developed just where we would expect an alkali-rich product on Lambert's hypothesis.

Thus each alternative is fraught with difficulties. On the whole the postulate of soda-rich bands seems to account best for the structural relations of the crocidolite seams, and while the mechanisms suggested by Hall and by Du Toit to explain such local concentration of soda along certain bedding planes do not appear very plausible, a wholly satisfactory alternative explanation does not suggest itself. During the accumulation of the igneous solutions believed to have reacted with precipitation of silica and ferric hydrate, sodium silicate solution may have occasionally been

emitted in considerable excess and have become occluded in horizontal zones in the accumulating chemical sediment. With subsequent dehydration and regional metamorphism the soda in these zones would be concentrated and might enter into some combination with the other constituents to form interbedded soda-rich bands which subsequently developed into crocidolite seams. This possibility receives support from a laboratory experiment in which the supposed precipitation of ferric hydrate by sodium silicate was imitated, and abundant soda obtained in the precipitate. While admittedly speculative this suggestion is put forward *faut de mieux* in the hope of stimulating critical interest in the difficult problem.

With regard to water, the last constituent to be considered, the analyses show that even the rather strongly metamorphosed magnetite-quartzite still contains about 3 per cent of water, while the ferruginous cherts adjoining the crocidolite seams contain about 6 per cent of this constituent. Crocidolite itself holds around 3 per cent of water. As the ironstones have undoubtedly been losing water since their deposition as chemical sediments, we may conclude with safety that interstitial water was present in the ironstones in amply sufficient amount to account for the proportion of water now combined in crocidolite. We are thus led to the conclusion that all the chemical components of crocidolite pre-existed in the ironstones *in situ*; in the case of soda, however, the evidence is not strong, and the view that soda is a foreign constituent cannot be definitely dismissed.

In regard to amosite the situation is different. Typical ash-gray amosite from the Transvaal is essentially a ferrous silicate with notable amounts of sesquioxides, magnesia and lime, less water than crocidolite and only traces of alkalis. Hall clearly shows that the amosite occurrences lie in the contact aureole of the Bushveld Complex (1918 B, p. 121), and it is impossible to resist the conclusion that the chemical dissimilarity existing between amosite and the country rock and the exceptional fibre-length exhibited by amosite are due to the fact that asbestos formation in the Transvaal was controlled by hydrothermal solutions emanating from the igneous mass after intrusion.

3. THE CONDITIONS ATTENDING THE FORMATION OF AMPHIBOLE-ASBESTOS

In the preceding section it was concluded that all the constituents of the crocidolite seams were present *in situ* in the ironstones; this implies the conclusion that the crocidolite seams were formed by molecular reorganization without essential transfer of material, following a change of physical conditions and a consequent displacement of chemical stability. To discover approximately what these conditions probably were we must be guided by the known conditions attending successful laboratory syntheses of amphibole, and by some geological considerations.

The difficult synthesis of amphibole was first achieved by Chrustschoff (1891) who obtained measurable prismatic crystals of hornblende by preparing the appropriate constituents chemically in the form of an aqueous gel which was heated in special stout exhausted glass bulbs for three months at about 550°C. Similarly Allen, Wright and Clement (1906) obtained minute fibres of amphibole with chemically prepared charges and water contained in a platinum crucible placed in a steel bomb and heated at 375–475°C for three to six days. These experiments show that the presence of water vapor is essential for the formation of amphibole, and that charges of the appropriate materials will combine at moderate temperatures and consequent pressures acting through periods negligibly short compared with geological time. They also show, as would be expected, that with lower temperatures and short runs fibres are formed, and that with higher temperatures and longer runs well developed crystals are obtained.

It is hard to estimate the quantitative effect of the time factor on the temperature required to effect such chemical changes. Certain it is, however, that given almost indefinite time the temperature at which the amorphous components of amphibole will combine will be very much lower than that required in a laboratory synthesis occupying only a few days. As crocidolite rarely develops beyond the fibrous condition we may further conclude that the temperature which obtained in the ironstones when the reorganization to crocidolite took place was near the lower extreme of the stability range of that mineral. Therefore, in view of the complete absence of evidence of severe thermal or contact metamorphism in the ironstones of the Cape Province, the very extensive and uniform nature of the crocidolite development, and

the considerations just given, it seems probable that the development of crocidolite was accompanied by a very moderate rise of temperature, such as would be produced by simple burial to moderate depths.

In addition to elevated temperatures, pressures above atmospheric are essential for the production of amphibole. Hornblende is perhaps the most familiar product of metamorphism induced by directed stress in rocks of basic composition; but such conditions would have converted the entire ironstone formation into amphibolite. In the present case we are clearly concerned not with directed stress, but only with uniform pressure resulting from the load of superincumbent strata and with the hydrostatic pressure necessary to inhibit the escape of water vapor at the prevailing temperature. Water vapor at a few hundred degrees centigrade is undoubtedly a very penetrating fluid and one might well question the retention of interstitial rock moisture at such temperatures, and therefore the formation of amphibole in the manner suggested. But colloidal materials have the property of retaining water at considerable temperatures at atmospheric pressure, a fact that was brought out in the laboratory experiment mentioned in connection with the origin of the ironstones. The colloidal precipitate obtained, even after heating to 350°C at atmospheric pressure, yielded over 3 per cent of water on ignition. Many rocks and minerals exhibit the same property.

We thus arrive at the conception of the crocidolite-bearing ironstone formation being buried under younger sediments, experiencing a consequently moderate rise of temperature and pressure greatest at the base and decreasing progressively upwards, and suffering a "sweating" process which resulted in molecular reorganization just sufficient to permit the union of amorphous silica, iron oxides, soda, magnesia and water dominantly in the lower horizons along bedding planes inferred to have been initially rich in soda. These conditions were also sufficient to promote some conversion of chert to quartz and amorphous iron oxide to magnetite, and occasionally to permit the growth of crocidolite to extend beyond the fibrous stage to an acicular condition.

4. THE ORIGIN OF CROSS-FIBRE STRUCTURE

The familiar cross-fibre structure of asbestos seams presents a problem which has attracted considerable attention and has given

rise to a variety of explanations. Minerals which assume fibrous form are also commonly found in well-developed crystals; thus when the fibrous condition is developed the explanation lies not in inherent habit but in special conditions of growth. To enquire into these conditions in the case of amphibole-asbestos and to ascertain if possible the cause of the typical common orientation of the fibres normal to the surfaces bounding the asbestos seams is the object of this section.

The beginnings of crystallization in amorphous media are marked by the development of crystallites so minute that their reaction to polarized light is inappreciable. Thus in acid volcanic glasses we find globulites, margarites, trichites and various plumose, arborescent and fibrous bodies representing incipient crystallization which was checked by the chilling of the glass. Similarly in natural and artificial glasses the inherent tendency to crystallize slowly overcomes the great viscosity of glass in the cold and devitrification proceeds with the development of similar fibrous crystallites. In palagonite, which is ideally the hydrogel of sideromelane (Author, 1926, p. 74), fibrous crystallites readily develop; and in general, minerals which crystallize from hydrogels, such as chalcedony and kidney ore, fibrous structure is displayed.

In the ironstones the beginnings of crocidolite formation are seen in the blue, sensibly amorphous bands which Klaproth called *Blau-Eisenstein*, and are referred to by Hall as *potential crocidolite*; these bands have been shown to have the same chemical composition as crocidolite. In the sections studied, every stage was seen from these unorganized blue bands to seams composed of wholly crystallized material ranging from the finest hairs to stout needles; and the conclusion is inevitable that the fibrous seams developed from sensibly amorphous, blue bands of incipient crocidolite. The fact that the fibrous condition is the dominant one, the incipient and acicular phases being now only slightly represented, may reasonably be taken to show that when crocidolization had in the main reached the fibrous stage the conditions which promoted this change were withdrawn, and further integration of fibres to form stout needles was largely inhibited. As the products of crocidolization display the structural features peculiar to the products of crystallization in many known amorphous media containing the necessary components *in situ*, the hypothesis that crocidolization proceeded by molecular organization in a

hydrated amorphous aggregate containing the necessary constituents in place receives support.

To explain the persistent orientation of asbestos fibres normal to the planes of the seams two principles, in general, have been invoked: first, that provided a growing crystal have restricted contact with the saturated solution from which it is growing, by virtue of the linear force of crystallization this crystal will continue to grow where it is in contact with saturated solution even against strong mechanical resistance; and second, that when a growing crystal wholly in contact with saturated solution meets mechanical obstruction as a result of its growth, the pressure developed at the contact increases solubility and checks further growth at that point, and the crystal continues to grow in the direction of least resistance.

The first principle is at the root of Taber's general theory of vein formation, based on experimental work on crystallizing salts, applied to the case of serpentine asbestos, and extended to cover the case of other minerals including crocidolite (1916; 1917; 1918 A, B; 1919; 1924; 1926). Taber partly immersed porous porcelain cups in concentrated solutions of various salts. Fibrous crystals commenced to grow from the walls of the cups and occasionally within the walls; in the latter case the growing crystals produced rupture with formation of cross-fibre veins. Incorporating these results, Taber's hypothesis is briefly as follows: "... that all cross-fibre veins are formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the inclosing walls; and that the fibrous structure is to be attributed largely to the physical conditions which have limited crystal growth to a single direction" (1917, p. 1985). On this hypothesis the solution from which the vein mineral is growing reaches the mineral only through the walls of the vein. Thus, in spite of the tendency for the pressure developed at the terminations of the growing fibres to inhibit further growth in the direction of the walls, as solution reaches the fibres only from this direction growth will continue with forcible displacement of the walls providing the concentration of the solution be sufficiently increased to keep pace with the increase of solubility produced by this pressure.

Taber's hypothesis as applied to crocidolite has many implications which are irreconcilable with known facts. If crocidolite

seams were formed by the forcible displacement of their walls then we would expect to find close sympathy in the irregularities of the two walls of a seam, especially in narrow seams. But when crocidolite seams are not bounded by parallel planes they are typically defined by one plane surface and one corrugated surface, so that in sections transverse to the bedding the crocidolite appears in short, sometimes almost disconnected, pod-like bodies; and within the space of a hand-specimen the bedding planes on either side will be perfectly straight. Such a structure cannot be explained by displacement of the walls. Again, if Taber's mechanism results in cross-fibre structure, then crocidolite seams should invariably have possessed this structure from the first; but many seams are still in the incipient, non-fibrous, unoriented condition, and there are good reasons for believing that all the cross-fibre seams originated in this condition. Furthermore, the basic postulate of Taber's hypothesis, namely of solutions of crocidolite migrating transversely to the bedding is difficult to accept. As far as we know, amphiboles cannot be taken into solution except under fusion conditions, and it is quite certain that such conditions never obtained in the ironstones which still consist largely of uncombined silica and iron oxides, materials which flux at moderate fusion temperatures. And finally, granting transversely migrating solutions of crocidolite, there is no evident reason why deposition should always take place along planes parallel to the bedding. For these reasons Taber's theory of cross-fibre vein formation is believed to be inapplicable to the South African crocidolite.

Other explanations of the cross-fibre habit of asbestos are directed mainly towards providing a means whereby a relief of pressure can be attained transversely to the seams, thus inducing the mineral to grow in a cross-fibre manner according to the second principle stated above. Merrill suggests that shearing action may account for the cross-fibre habit of asbestos in many cases (1895, p. 289). Differential movement of the walls in the plane of a growing asbestos seam would certainly produce the desired relief of transverse pressure with increase of lateral pressure, and tend to produce an oblique structure. In the present collection, however, seams with obliquely oriented fibres are exceptional, and in these cases the skew orientation is probably the result of later shearing. In the case of the chrysotile-asbestos of Black Lake,

Thetford area, Quebec, Graham believes that the thermal contraction of the peridotite batholith may have been greater than the expansion due to concurrent serpentinization, and that therefore fractures in the mass tended to widen and thus to encourage cross-fibre growth of chrysotile (1917, p. 195). But such a mechanism is manifestly inapplicable to the sedimentary ironstones.

Hall infers that the South African crocidolite and amosite was first deposited in the mass-fibre condition. With continued growth favorably placed fibres would tend to thrust the walls apart thus encouraging the remaining material to develop fibres transverse to the plane of the seam; in addition, lateral pressure due to mutual interference of growing crystals, unequal pressures arising from volume changes, and unequal solution supply are suggested as contributing to the final cross-fibre structure (1918 B, p. 123). Thus, while recognizing that the transverse orientation of the fibres in amphibole-asbestos seams is not a primary property of the seams, Hall's explanation appears to rely at once on the power of a crystal to grow against mechanical resistance, and on the tendency for crystals to grow in the direction of least obstruction.

The tendency for crystallizing bodies to develop structures normal to their bounding surfaces is a common one. In the case of crystallization from igneous fusion this tendency is illustrated by the familiar columnar structure developed normal to the cooling surfaces of intrusive rock-bodies, and by the orientation of the dendrites which develop in steel ingots normal to the chill-surfaces of the moulds. Similarly certain salts, such as common salt, copper sulphate and potash alum, commonly develop cross-fibre structure on crystallization from aqueous solution in natural veins. The satin-spar varieties of gypsum and calcite and the mineral celestite frequently develop the same feature. Certain hydrous silicates, such as prehnite, stilbite and pectolite, and other minerals which have crystallized from gels rather than from solution, such as goethite, serpentine and chalcedony, commonly develop fibrous or platy structure in which the long axes of the crystalline units lie normal to the bounding surfaces of the mineral body. The perpendicular relation between fibrous structure and the bounding surfaces of mineral bodies possessing this structure is thus too consistent to be insignificant, and therefore we can hardly escape the conclusion that the bounding surfaces in some way exert a control over the orientation of the fibres.

In the case of minerals which crystallize from normal or colloidal solutions, crystallization is accompanied by loss of water. If this should take place in a totally enclosed cavity, or in an extensive vein completely filled with the solution or gel from which precipitation is taking place, the escape of water necessary to produce saturation and precipitation must ultimately take place through the walls of the cavity or vein. In this way the bounding surfaces of the mineral body become "drying-surfaces," strictly analogous to cooling-surfaces in their effect on precipitation and orientation of structure.

In the analyzed examples the ferruginous cherts in the neighborhood of crocidolite seams contain a total of 5.90 per cent of water; incipient crocidolite, inferred to be the earliest product of crocidolitization contains 3.46 per cent of water; the fine cross-fibre crocidolite believed to have resulted from further organization of the incipient material, carries 2.89 per cent of water; while the stout acicular material, representing further crystalline integration in fibrous seams, yields 2.77 per cent. of water. Crocidolitization is thus accompanied by a progressive loss of water, which must have escaped through the walls of the seams. The change from the incipient to the fibrous condition would thus take place first at the contacts of the seams with their walls. Just as crystals of ice grow out perpendicularly to the walls of a tank of water from which heat is being withdrawn, the first thin film of crocidolite changing from the incipient to the fibrous condition would arrange itself with its fibres normal to the controlling wall-surfaces. Where possible, crystalline accretion takes place in optical continuity with existing crystals of the same material; and therefore the lead set by the first thin layers of perpendicularly oriented fibres would determine the orientation of the remainder of the seam.

To conclude, although the ultimate nature of the force or reaction of forces, by virtue of which cooling- or drying-surfaces of a mineral body control the orientation of fibres developing at such surfaces, has not been found, the existence of this control cannot be gainsaid. On the theory of origin of crocidolite developed, the orientation of the fibres normal to the walls of the seams is believed to be an effect of this proved, although not fully understood, control.

VI. SUMMARY OF OBSERVATIONS AND CONCLUSIONS

1. MINERALOGICAL

(a) The South African asbestos-bearing ironstones range from cryptocrystalline ferruginous cherts to fine-grained magnetite-quartzites in which detrital grains cannot be detected and crystalline structure appears to be secondary.

(b) Two new analyses show that the ironstones consist of silica, iron oxide largely or wholly peroxidized, and water, with less than three per cent. of other constituents.

(c) The dominant asbestos variety is blue crocidolite occurring chiefly in thin, extensive, cross-fibre seams conforming strictly with the bedding of the ironstones. To a subordinate extent crocidolite occurs also in a non-fibrous, "incipient" condition, and in seams of stout needles—the "acicular" condition.

(d) New analyses of the three phases of crocidolite conform tolerably with the metasilicate: $3\text{H}_2\text{O} \cdot 2\text{Na}_2\text{O} \cdot 6(\text{Fe}, \text{Mg})\text{O} \cdot 2\text{Fe}_2\text{O}_3 \cdot 17\text{SiO}_2$, in which H_2O is wholly basic. To maintain a better balance between silica and the bases in these analyses, and in other analyses of amphiboles carrying notable proportions of sesquioxides, an interpretation in terms of the three molecules: $\text{R}_2\text{O}_3 \cdot \text{RO} \cdot \text{SiO}_2$, $\text{R}_2\text{O}_3 \cdot \text{RO} \cdot 4\text{SiO}_2$; and $\text{RO} \cdot \text{SiO}_2$ is advocated.

(e) The following new optical data were obtained for crocidolite: $\alpha = 1.698$; $\beta = 1.699$; $\gamma = 1.706$; X = indigo; Y = yellow; Z = indigo; $X \wedge c = 0^\circ$; $Z = b$; X and Y may possibly be interchanged. Although sensibly orthorhombic crocidolite is regarded as a fibrous form of riebeckite and retained as a monoclinic amphibole in which the extinction angle is zero.

(f) The long-fibred, ash-gray asbestos, amosite, typically developed in ironstones within the contact aureole of the Bushveld Intrusion, proves to be an orthorhombic amphibole with ferrous oxide as the dominant base. Carrying sesquioxides intermediate in amount between the ideally sesquioxide-free anthophyllites and the highly aluminous gedrite, amosite is sustained as a mineral species. The composition of amosite is expressed in the same general manner devised for crocidolite (d). A greenish, short-fibred form of amosite carries about 11 per cent of lime.

(g) The following new optical data were obtained for typical ash-gray amosite: mean of α and $\beta = 1.675$; $\gamma = 1.702$; mean of X and Y, pale greenish brown; Z, pale brownish green; $Z = c$. Greenish amosite gave: mean of α and $\beta = 1.663$; $\gamma = 1.680$; mean of X and Y, grayish green; Z, grass green; $Z = c$.

2. GENETIC

(a) On the grounds of typical non-detrital character and uniquely simple chemical composition, the ironstones are regarded as having originated as chemical precipitates deposited in an extensive marine basin. Occasional intercalations of detrital sediments are related to oscillations of the floor of this basin, varying its extent and occasionally bringing it within the range of mechanical sedimentation.

(b) It is shown that certain essential differences of constitution and geological relationship exist between the ironstones of South Africa and those of the Lake Superior region; and that therefore the hypothesis of Van Hise and Leith to explain the origin of the North American occurrences is not directly applicable to the South African problem.

(c) The view that marine fixed chlorine originated in igneous emanations is briefly advocated and adopted. From analogy it is argued that the action of hot, submarine fumaroles carrying hydrochloric acid would result, in addition to alkali chlorides, in the contribution of ferric chloride and gelatinous silica to the seawater. Ammoniacal vapors and soluble alkali silicates are suggested as possible natural reagents to precipitate iron as ferric hydrate. On dehydration and induration the heterogeneous precipitate of silica and ferric hydrate would be converted into a rock substantially similar to a ferruginous chert.

(d) It is shown that, with exception of soda in the crocidolite belts, all the chemical constituents of crocidolite are present in adequate proportions in the ironstones. Of the alternate views: that crocidolitization was induced by soda-bearing solutions emanating from some postulated igneous source; or that crocidolitization took place along bedding planes inferred to have been initially rich in soda; the latter is adopted. The chief grounds for this decision are: that in the Transvaal, where asbestos formation was clearly induced by hydrothermal solutions from the Bushveld Intrusion, an alkali-free asbestos, amosite, is developed; that over the immense lateral extent of the crocidolite belts there is apparently little variation in the degree of crocidolitization; and that crocidolite seams unfailingly conform to the bedding of the ironstones while late veinlets of quartz and calcite frequently transgress.

(e) Crocidolitization is thus conceived as a mild, static, non-additive, metamorphic process resulting in the chemical union, along soda-rich bedding planes, of the necessary constituents already *in situ*. The process is described as a "sweating" action, facilitated by interstitial rock moisture, and induced by a moderate rise of temperature and pressure such as would result from simple burial of the ironstones to moderate depths.

(f) The unorganized, "incipient" condition, the typical fibrous condition, and the acicular condition, are regarded as progressive stages in the crystalline integration of crocidolitized bands. The transverse orientation of the fibres is therefore believed to have developed after crocidolitization was virtually completed.

(g) Taber's general theory of cross-fibre vein formation, involving deposition through the walls of the vein from solutions in the wall-rock, and forcible displacement of the walls by growing fibres, is shown to be inapplicable to the South African asbestos.

(h) The cross-fibre structure of the asbestos seams is related to the little-understood but undeniable control which bounding surfaces commonly exert on the orientation of the structure of fibrous minerals crystallizing from solutions or gels.

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VIII. EXPLANATION OF PLATES

PLATE I

Fig. 1. Asbestos-bearing ironstones at Kliphuis, 8 miles north of Prieska, Cape Province. The dumps of the Kliphuis Mine are seen in the middle of the picture *Photo. by Charles Palache.*

Fig. 2. A closer view of the asbestos-bearing ironstones at Kliphuis, 8 miles north of Prieska, Cape Province. *Photo. by Charles Palache.*

PLATE II

Fig. 1. Banded ironstone (13000) from Prieska Kopje. This rock, which consists essentially of finely granular quartz and magnetite, is a mildly metamorphosed facies of the normal, cryptocrystalline, ferruginous chert. Comparable with analysis I, TABLE II. Ordinary light; 20 diameters. *This and subsequent photomicrographs by the author.*

Fig. 2. Incipient crocidolite in ferruginous chert (13023), from Kliphuis. The dark areas are brown, cryptocrystalline ironstone, while the light areas are composed of minute units of blue crocidolite. These are unoriented, and therefore do not give the strong simultaneous pleochroism of similarly oriented fibres. Analysis II, TABLE V. Ordinary light; 20 diameters.

PLATE III

Fig. 1. Crocidolite seam in bleached ironstone (13046), from Keikamspoort. The formation of crocidolite and magnetite in wavy bands has been accompanied by some extraction of iron from the enclosing chert. The magnetite is regarded not as representing pre-existing bands of ore displaced by the growing crocidolite, but as a contemporaneous product. Two ironstone "cones" are seen projecting into the asbestos seam. Ordinary light; 20 diameters.

Fig. 2. Seam of acicular crocidolite (13047), from Keikamspoort. This is the material from which the fullest optical data were obtained. Comparable with analysis III, TABLE V. Ordinary light; 20 diameters.



FIG. 1



FIG. 2

PLATE I

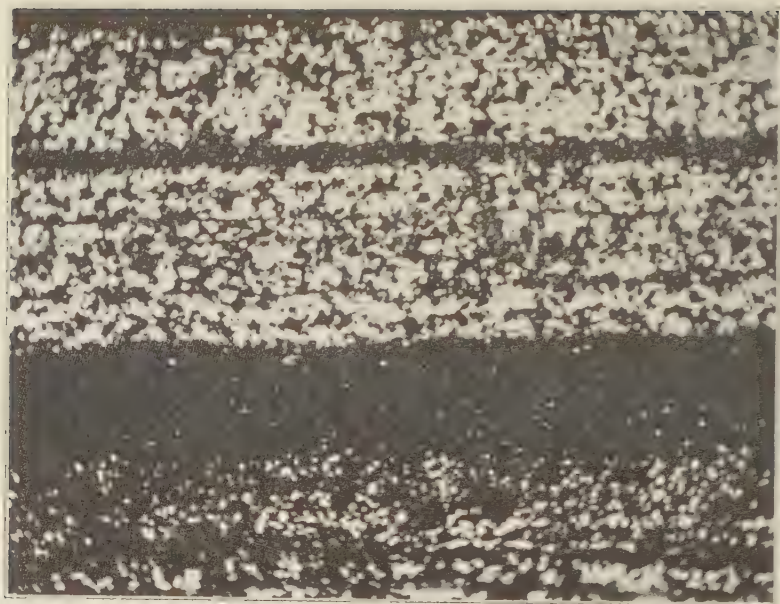


FIG. 1

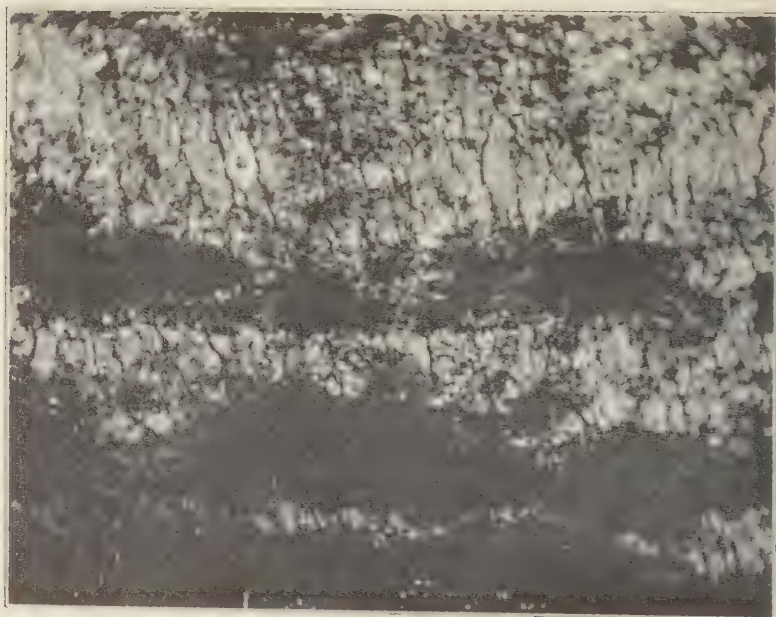


FIG. 2

PLATE II

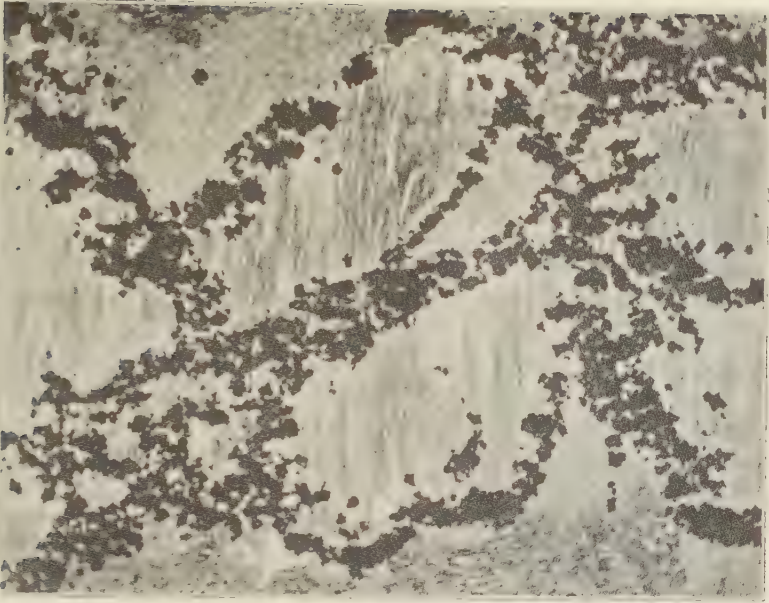


FIG. 1



FIG. 2

PLATE III

THE CHEMISTRY, OPTICS, AND GENESIS OF THE
HASTINGSITE GROUP OF AMPHIBOLES

MARLAND BILLINGS

INTRODUCTION. The chief amphiboles found in the alkaline rocks are riebeckite, various members of the hastingsite group as defined in the present paper, and barkevikite. Riebeckite is found in rocks supersaturated with silica, such as alkaline granites, comendites, and paisanites. Members of the ferrous end of the hastingsite group are found in hastingsite granites, nordmarkites, and nephelite syenites. Barkevikite and the magnesian members of the hastingsite group are found in diorites, essexites, and related calcic rocks. The present paper is concerned only with the hastingsite group, for which two new analyses are given.

Although a number of chemical analyses of the hastingsite group are available, the optical data are very incomplete. Data on the indices of refraction are particularly lacking. In order to correct these deficiencies the writer has obtained either the original specimen from which the chemical analysis was made or material as nearly identical as possible. It is indeed unfortunate that so many chemical analyses are published without adequate optical data. Mineralogists and petrographers should realize that a chemical analysis without such optical data does little to advance the science of petrography.

The writer is very much indebted to Dr. E. S. Larsen of Harvard University for permission to use the unpublished chemical and optical data for an amphibole (magnesian hastingsite) from Iron Hill, Colorado. Dr. E. V. Shannon has kindly sent me a specimen of the Custer County ferrohastingsite which he analyzed. (5)*

FERROHASTINGSITE.† Ferrohastingsite was originally described as hastingsite from the nephelite syenites of Hastings County, Ontario, by Adams and Harrington. (1) Since then a number of analyses of ferrohastingsite have been published from various localities and we may now safely say that this and closely related amphiboles are the common amphiboles in the nephelite syenites, nordmarkites, and hastingsite granites. The available chemical and optical data are given in TABLE I.

* See the bibliography at the end of this paper.

† The basis of the nomenclature of the hastingsite group is discussed on a later page.

TABLE I. CHEMICAL DATA ON FERROHASTINGSITE

	a.	b.	c.	d.	e.	Average
SiO ₂	34.184	37.49	37.40	38.50	36.86	36.96
Al ₂ O ₃	11.527	10.81	12.34	10.88	12.10	11.55
Fe ₂ O ₃	12.621	7.52	4.16	6.70	7.41	7.70
FeO	21.979	25.14	25.84	27.28	23.35	24.77
MgO	1.353	1.35	2.20	1.40	1.90	1.64
CaO	9.867	9.77	9.72	11.30	10.59	10.27
Na ₂ O	3.290	2.06	1.80	1.22	3.20	2.31
K ₂ O	2.286	1.91	1.36	1.66	1.20	1.68
H ₂ O+	0.348	2.01	0.00	1.27	0.60	0.62
H ₂ O—			0.60	0.00	0.70	0.43
MnO	0.629	0.95	1.24	tr.	0.77	0.72
TiO ₂	n. d.	0.86	3.20	tr.	n. d.	1.35
Total	98.084	99.87	99.86	100.21	98.68	100.00
Sp. Gr.	3.433		3.375 at 4°C.		3.5	3.4

(a) Ferrohastingsite from nephelite syenite, Dunganon, Hastings County, Ontario (1). The optical data were obtained by the present writer on hastingsite from a nephelite syenite found near Gooderham, Ontario. The incomplete optical data given by Graham (2) checks sufficiently with that obtained by the author to indicate that the material is essentially the same as that analyzed.

(b) Ferrohastingsite from nephelite syenite, Almunge, Sweden. (3) The optical data have been obtained in part by the present writer from a canadite (nephelite syenite) pegmatite. 2V has been calculated from 2E as given by Quensel (3), the extinction angle obtained by me is much less than that given by Quensel. The ferrohastingsite found in the nordmarkites of Almunge has an orientation $V = b$ and an optic angle about $2V = 45^\circ$.

TABLE 1A. OPTICAL DATA ON FERROHASTINGSITE

	a	b	c	d	e	Average
Indices $\left\{ \begin{array}{l} \alpha \\ \beta \\ \gamma \end{array} \right\}$	1.705 1.731 1.732	1.697 1.713 1.714	1.698 1.719 1.722	1.693 1.710 1.713		1.698 1.720 1.723
Optic angle (2V)	about 25°	about 16°				
Dispersion	strong $\rho < \nu$	strong $\rho < \nu$	47° medium $\rho > \nu$	small		small
Orientation	$Z = b$	$Z = b$	$Y = b$	$Y = b$	$Y = b$	strong to medium varies $Z = b$ in nephelite syenites $Y = b$ in quartz- bearing rocks.
Extinction angle	$Y \wedge c = 13^\circ$	$Y \wedge c = 15^\circ$	$Z \wedge c = 20^\circ$	$Z \wedge c = 17^\circ$	$Z \wedge c = 9^\circ$	$Z \wedge c = 9^\circ$ to 20° $Y \wedge c$
Pleochroism $\left\{ \begin{array}{l} X \\ Y \\ Z \end{array} \right\}$	yellow deep greenish blue (almost opaque) deep olive green	yellow bluish green olive green	yellow olive green deep green	greenish brown brownish green smoky blue green	light olive green yellowish green bluish green deep bluish green (olive green)	yellow olive green (deep bluish green) deep bluish green (olive green) $Z = Y > X$
formula	$Z > Y > X$	$Y > Z > X$	$Y > Z > X$	$Z > Y > X$	$Z \bar{\bar{Y}} > X$	

The optical character is always negative.

- (c) Ferrohastingsite from porphyritic nordmarkite, Jackson, New Hampshire (4). W. H. Hersman of Glasgow, Scotland, analyzed the material for me. The optical data have been obtained from the same material as that analyzed. 2V was measured on the Federow stage and the error is not over three degrees. The mineral was separated from the rock by means of an electro-magnet and heavy solutions; it was at least 99 per cent. pure.
- (d) Ferrohastingsite from a contact (?) metamorphic limestone, Custer County, Idaho (5). The United States National Museum kindly loaned me for optical study a sample of the original material analysed by Shannon.
- (e) Ferrohastingsite (hudsonite) from a pegmatite, Cornwall, Orange County, New York (6). No specimens of this material were available to the writer, hence the original data given by Weidman, though incomplete, are quoted. $Z \wedge c$ is in the obtuse angle β .

TABLE II. CHEMICAL DATA ON FEMAGHASTINGSITE AND MAGNESIOHASTINGSITE

	f	g	h_1	h_2	\bar{g}
SiO ₂	38.04	38.633	39.23	39.23	43.30
Al ₂ O ₃	13.50	11.974	11.94	14.38	10.69
Fe ₂ O ₃	6.21	3.903	5.92	2.92	3.94
FeO	15.85	11.523	12.04	8.56	7.00
MgO	7.26	10.200	11.01	13.01	16.02
CaO	12.42	12.807	11.21	11.70	9.73
Na ₂ O	3.21	3.139	2.33	3.05	4.58
K ₂ O	1.68	1.489	0.99	0.98	0.66
H ₂ O+	n. d.	n. d.	{ 0.36	0.36	1.80
H ₂ O-	n. d.	n. d.		0.65	0.35
MnO	1.21	0.729	0.10	4.53	1.55
TiO ₂	1.06	5.035	7.99		
Total	100.44	99.432	99.54	99.37	99.62
Sp. Gr.	3.518 at 20°C	?	?	3.159 at 12.5°C	3.160 at 4°C
FeO/MgO	1.22	0.63	0.61	0.37	0.24

All of these minerals are biaxial negative. The FeO/MgO ratio is determined from the molecular proportions.

(f) Femaghastingsite from akerite, Cuttingsville, Vermont (10). Theoptical data were determined by the present writer on the original analyzed material. This amphibole is zoned in some crystals, the core having an extinction angle as high as 66°, the periphery as low as 52°. 2V as given in the table has been measured on the Federow stage for the more common unzoned variety and the error is not greater than one degree.

(g) Femaghastingsite from essexite, Mt. Johnson, P.Q.(7). The optical data have been determined on material that is from the same mountain. 2V has been measured on the Federow stage; the error is not greater than three degrees.

TABLE IIA. OPTICAL DATA ON FEMAGHASTINGSITE AND MAGNESIOHASTINGSITE

	f	g	h_1 and h_2	i
Indices $\begin{cases} \alpha \\ \beta \\ \gamma \end{cases}$	1.679	1.670	1.676	1.653
	1.694	1.692	1.692	1.663
	1.698	1.703	1.705	1.670
Optic angle (2V)	60° (52°–66°)	80°	76° (75°–81°)	64°
Dispersion	medium $\rho < \nu$	medium $\rho < \nu$	Perceptible $\rho > \nu$	low
Orientation	$Y = b$	$Y = b$	$Y = b$	$Y = b$
Extinction angle	$Z \wedge c = 11^\circ$	$Z \wedge c = 15^\circ$	$Z \wedge c = 16^\circ$	$Z \wedge c = 40^\circ$
Pleochroism $\begin{cases} X \\ Y \\ Z \end{cases}$	light brown	light brown	yellow	pale yellow
	brown	brown	deep brown	green
	greenish brown	brown, hint of green	deep brown	green
Formula	$Y > Z > X$	$Y > Z > X$	$Y = Z > X$	

(h₁) Titaniferous femaghastingsite from diorite, Montreal (9). NiO 0.04 and SrO 0.01, making total 99.59.

(h₂) Magnesiohastingsite from essexite, Montreal (8).

(h₁) and (h₂) According to Bancroft and Howard (9) these are the common amphiboles of the gabbros, diorites, wehrlites, and pyroxenites of Mount Royal. The optical data given above were determined by the author on an amphibole from an essexite. From a consideration of the optics of the whole hastingsite group I am inclined to believe that the optics were determined on the femaghastingsite type. 2V has been measured on the Federow stage; the error is not over two degrees. In those crystals that are zoned the core has a higher axial angle than the periphery.

(i) Magnesiohastingsite from metamorphosed limestone, Iron Hill, Colorado. The optics have been determined on the same material as that analyzed. This is a new analysis made by W. H. Herdman of Glasgow, Scotland, on material collected by Dr. E. S. Larsen. The optics have been determined by Dr. Larsen, with the exception of 2V, which was measured by the writer on the Federow stage; the error is not over one degree. Although this is distinctly a metamorphic mineral, it is associated with nephelite rocks.

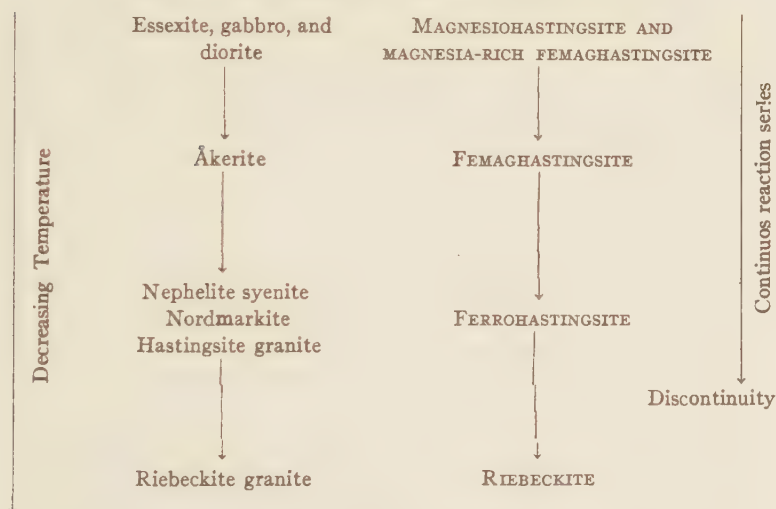
MAGNESIOHASTINGSITE AND FEMAGHASTINGSITE. Adams(7), Harrington(8), and Bancroft and Howard(9) have described amphiboles from the essexites of Mt. Johnson, P. Q., and Mount Royal, P. Q., which are chemically identical with ferrohastingsite except that part of the ferrous iron of ferrohastingsite is isomorphously replaced by magnesia (see *g* and *h* in TABLE II). An even more extreme member of the group has been found by Dr. E. S. Larsen in a metamorphic rock from Iron Hill, Colorado (*i* in TABLE II). Although closely allied, both chemically and petrologically, to ferrohastingsite, the distinctly higher content of magnesia necessitates a different designation. The classification of the hastingsite group is most logically based on the ratio of ferrous iron to magnesia (molecular proportions); if FeO/MgO exceeds two, the mineral is ferrohastingsite; if FeO/MgO is less than two, but greater than one-half, the mineral is femaghastingsite; if FeO/MgO is less than one-half, the mineral is magnesiohastingsite. The original hastingsite of Adams and Harrington (1) may thus be designated ferrohastingsite. The metamorphic amphibole from Iron Hill and the amphibole from the essexite of Mt. Royal may be considered magnesiohastingsite. The amphiboles from the essexite at Mt. Johnson and from the âkerite at Cuttingsville, Vermont (10), belong to the intermediate type, femaghastingsite (*f* and *g* in TABLE II).

RELATION OF CHEMICAL COMPOSITION AND OPTICAL PROPERTIES. From the above analyses and optical data the following facts are apparent. Most of the oxides in the hastingsite group are relatively constant with the exception of ferrous iron and magnesia which apparently isomorphously replace each other (see TABLES I and II). $\text{RO}_2(\text{SiO}_2 + \text{TiO}_2)$ increases toward the magnesia end of the series due to the greater weight of iron relative to magnesium. TiO_2 is somewhat variable, being particularly high in the calcic rocks of Quebec. The increase in magnesia affects the optics in the following manner: $2V$ increases, the indices of refraction decrease, and the specific gravity is reduced.

PETROLOGICAL SIGNIFICANCE. From the analyses available there seems to be a very definite relation between the composition of the amphibole and the rock in which it occurs. Magnesiohastingsite evolves into ferrohastingsite along the lines shown in the diagram, TABLE III. The observations made on the femag-

hastingsite in the åkerite from Cuttingsville are particularly significant, for in this case we observed an intermediate type with a core (older phase) tending toward magnesiohastingsite and a periphery (younger phase) tending toward ferrohastingsite. Similar relations were found in one of the Mt. Royal amphiboles. Ferrohastingsite may originate not only as a reaction product from magnesiohastingsite and femaghastingsite, but it may also be directly precipitated from the magma or may originate as a reaction product from hedenbergite (4).

TABLE III. THE GENESIS OF THE HASTINGSITE GROUP.



Although the analyses considered in this paper have of necessity been chosen from a number of petrographic provinces, five of the most significant analyses come from the late-Devonian New England-Quebec alkaline province. They are the ferrohastingsite from Jackson, New Hampshire, the femaghastingsite from Cuttingsville, Mount Johnson, and Mount Royal, and the magnesiohastingsite from Mount Royal.

TABLE IV. CHEMICAL AND OPTICAL DATA ON ALKALI-HASTINGSITE

	j	k
SiO ₂	35.42	37.80
Al ₂ O ₃	8.89	12.89
Fe ₂ O ₃	9.73	6.14
FeO	24.48	12.55
MgO	0.17	4.10
CaO	6.93	13.64
Na ₂ O	5.13	5.26
K ₂ O	3.23	3.24
H ₂ O+ H ₂ O- }	3.15	n.d.
MnO	1.17	n.d.
TiO ₂	1.34	4.54
Total	99.64	100.16
FeO/MgO	85.00	1.71
Indices { α	1.699	1.680
{ β	1.719	1.695
{ γ	1.721	1.705
Optic angle (2V)	about 36°	large
Dispersion		strong $\rho < \nu$
Orientation	Y = b	Y = b
Extinction angle	Z \wedge c = 20°	Z \wedge c = 11°
Pleochroism { X	greenish yellow	light yellowish brown
Y	olive green	brown
Z	bluish green	deep brown
Formula	Y $\bar{\leq}$ Z > X	Z > Y > X

Both minerals are biaxial negative.

The FeO/MgO ratio is determined from the molecular proportions.

(j) Alkali-ferrohastingsite from umptekite (quartz-bearing), Beverly, Mass. (11). The value for 2V has been calculated from 2E as given by Wright; the rest of the data have been determined from material in which Z \wedge c, $\gamma - \alpha$ and $\gamma - \beta$ checked with the data given by Wright.

(k) Alkali-femaghastingsite from camptonite at Campton Falls, New Hampshire (12). The optical data were determined on the amphibole from what is probably the same dike as that which yielded the material for the chemical analysis. The optics are very similar to those for the femaghastingsite from Cuttingsville and it will be noted that the chemical composition is not essentially different.

ALKALI-HASTINGSITE AND RELATED TYPES. In the alkaline rocks we also find a group of alkali-rich amphiboles which may have optical properties essentially identical to those of hastingsite despite the fact that some of the oxides differ by four per cent. In other words, even after the optical properties have been determined we can not state the chemical composition very definitely. If we compare the optical data of the alkali-ferrohastingsite from Beverly, Massachusetts, with the data on the ferrohastingsite from Jackson, New Hampshire, we see that they are almost identical; there is, nevertheless, considerable difference in chemical composition. The group is characterized by an alkali content of more than six per cent by weight.

SUMMARY. We may summarize the results as follows:

1. The hastingsite group comprises the common amphiboles of the alkaline rocks with the exception of the alkali granites, in which riebeckite may be present instead of hastingsite. Members of the hastingsite group are also found as contact alteration products in limestones.

2. Ferrohastingsite has a relatively definite chemical composition. The most striking chemical properties are the low silica (37%) and high ferrous iron (25%). Lime and alumina are abundant (each about 11%); ferric iron makes up about 8%; the alkalis are low, the total never exceeding six per cent by weight. Magnesia is very low. The specific gravity is high (about 3.45).

3. The most striking optical properties of ferrohastingsite are the high indices and the small optic angle. The optical orientation varies; the limited available data suggests that the mineral from the quartz-bearing rocks has $Y=b$, whereas that from the nephelite-bearing rocks commonly has $Z=b$.

4. Femaghastingsite and magnesiohastingsite are chemically similar to ferrohastingsite except that part of the ferrous iron is isomorphously replaced by magnesia.

5. The optical properties of magnesiohastingsite and femaghastingsite are determined largely by the magnesia-ferrous iron ratio. With increase in ferrous iron the indices and specific gravity increase but the optic angle decreases.

6. A definite evolution in the amphiboles of the alkaline rocks may be seen. Magnesiohastingsite and magnesia-rich femaghastingsite occur in the essexites and diorites, femaghastingsite in the åkerites, and ferrohastingsite in the nephelite syenites,

nordmarkites, and alkali granites. In the final stages of differentiation the concentration of silica and soda becomes so great that a completely new type of amphibole, riebeckite, is formed.

7. A number of alkali-rich amphiboles are also present in the alkaline rocks. These can not be readily separated by optical methods from the members of the hastingsite group.

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MINERALOGICAL NOTES ON FRANKLIN AND
STERLING HILL, NEW JERSEY

CHARLES PALACHE

The Harvard Mineralogical Museum has received, during the past year, very large additions to its series of specimens from Franklin Furnace, the study of which has added many new facts to our knowledge of a number of the Franklin minerals. The Stanton Collection, purchased after the death of Mr. Stanton and rich in the discoveries of the past few years, has been as yet only partly studied. The Canfield duplicates, purchased from the trustees, contained many interesting specimens. Most valuable of all, however, are the materials sent at frequent intervals by Messrs. Bauer and Jenkins, chemists of the New Jersey Zinc Company, for they are generally accompanied by careful chemical analyses and represent the newest discoveries both at Franklin and Sterling Hill.

The following notes, compiled by the author whose name alone appears in the title, rest upon such analyses and upon crystallographic and optical studies made by Messrs. L. W. Lewis and H. Berman.

They treat of the occurrence, crystallography, optical and chemical properties of the following minerals: azurite, bornite, cahnite, clinohedrite, clinozoisite, crocidolite, gageite, glaucocroite, hetaerolite, hodgkinsonite, leucophoenicite, manganite, quartz, smithsonite, sussexite, tephroite, tennantite, and willemite.

AZURITE. While long known at Franklin as a stain associated with small veins containing chalcopyrite, azurite was but recently found in crystallized specimens. In the Stanton Collection it is represented by material from both Franklin and Sterling Hill. The Franklin crystals occur in thoroughly oxidized vein material found in the mine in the 720 pillar on 200 level.

The small crystals are rich in forms. They line cavities in limonitic calcite along with malachite and fine rosettes of aurichalcite, the hydrous carbonate of zinc and copper.

The individual crystals are elongated parallel to the b axis with $\theta(\bar{1}01)$ dominant in the orthodome zone. The truncation is dominated by $d(\bar{2}43)$ and $p(021)$ as shown in Plate IV, figure 1, with the following forms present as small faces; $m(110)$, $\psi(\bar{3}01)$, and $h(221)$.

EXPLANATION OF PLATE IV

Fig. 1a. Azurite projection of a crystal showing the forms $a(100)$, $c(001)$, $\theta(\bar{1}01)$, $\psi(301)$, $m(110)$, $p(021)$, $d(243)$.

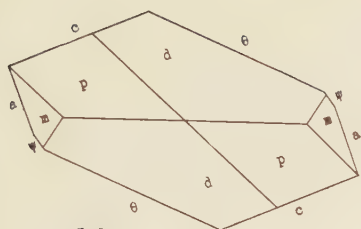
Fig. 1b. Azurite. The same crystal as 1a projected on $b(010)$.

Figs. 2a and b. Azurite. Clinographic and basal projections of a crystal showing the forms $c(001)$, $a(100)$, $\sigma(101)$, $\theta(\bar{1}01)$, $m(110)$, $h(221)$, $p(021)$, $l(023)$, $R(241)$, $e(524)$, $P(223)$, $\Re(034)$, $*(\bar{1}.3.24)$. The drawing is made with the b axis in front instead of the normal position.

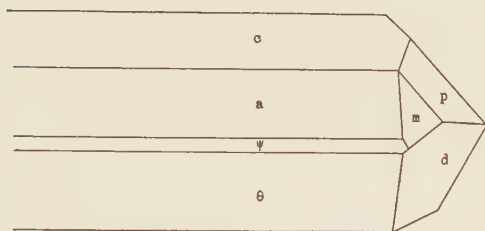
Figs. 3a and b. Azurite. Clinographic and basal projections of a crystal showing the forms $c(001)$, $a(100)$, $b(010)$, $\theta(101)$, $\sigma(\bar{1}01)$, $m(110)$, $p(021)$.

Fig. 4a. Cahnite. Photograph of a twin crystal.

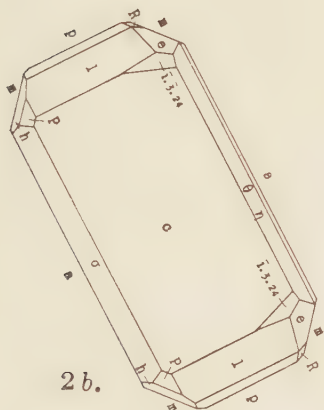
Fig. 4b. Drawing of the same crystal as shown in the photograph of 4a showing the forms $a(100)$, $m(110)$, $p(111)$, $o(1\bar{1}1)$.



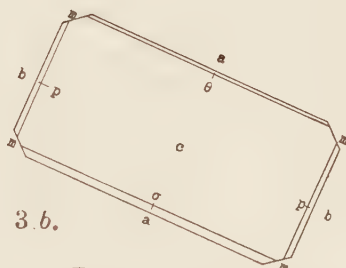
1 b.



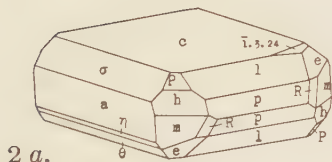
1 a.



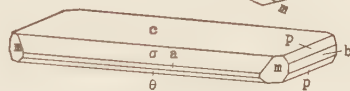
2 b.



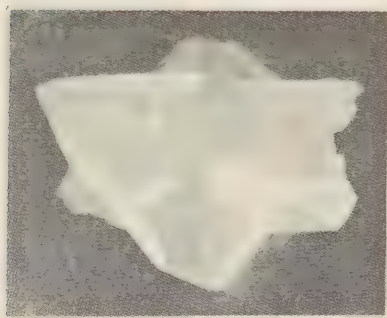
3 b.



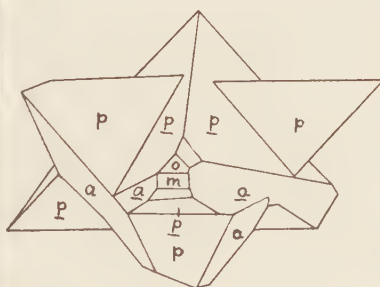
2 a.



3 a.



4 a.



4 b.

At Sterling Hill specimens of massive coarse granular franklinite ore were found intersected by veins of calcite and azurite which appear to be a replacement of the ore. As a whole, azurite followed calcite but the deposition of the two overlapped in part. The veins are generally granular but in a few cases cavities in the franklinite representing complete solution of large grains are lined with brilliant crystals of azurite.

Seven crystals were measured—the largest being 2 mm. in greatest length parallel to the orthodome zone. The faces were small and signals faint but the angles check closely with those calculated from the axes based on the measurements of Tsumeb crystals.¹ The crystals are flattened parallel to $c(001)$ with the orthodome and clinodome zones prominent. Plate IV, figure 2, illustrates a small, doubly terminated crystal found with ideal development. The following forms were identified on crystals of this type:

$c(001)$, $a(100)$, $\sigma(101)$, $\theta(\bar{1}01)$, $m(110)$, $h(221)$, $p(021)$,
 $l(023)$, $R(\bar{2}41)$, $e(\bar{5}24)$, $P(223)$, $\mathfrak{R}(034)$, and $*(\bar{1}.3.24)$

The form marked with an asterisk is an etch face occurring symmetrically developed on most of the crystals. Only on one crystal was it possible to get distinct signals and the readings were as follows:

	ϕ	ρ
Average	2°09'	6°38'
Calculated	0°21'	7°04'

The form is not considered of any value except as an interesting symmetrical and persistent occurrence of an etch face.

Plate IV, figure 3, illustrates the habit of some paper-thin plates of azurite flattened parallel to $c(001)$. The relative thickness is exaggerated in order to show the forms present as small faces.

BORNITE. The occurrence of bornite at Franklin is uncommon although some specimens of chalcopyrite were seen which seemed to contain minute grains of the darker colored bornite. The following analysis, however, made on a specimen from the mine at Franklin by the chemists of the New Jersey Zinc Company proves its presence although mixed with sphalerite:

¹ Palache and Lewis, *Am. Mineral.*, 12, April, 1927.

ANALYSIS OF IMPURE BORNITE BY L. H. BAUER

	Percentages	Mol. ratios	ZnS	Mol. ratios	Bornite Mol. ratios
Cu	38.16	.600			.600 = 5 × .120
S	28.38	.887		.420	.467 = 4 × .117
Fe	10.41	.186	.066	.420	.120 = 1 × .120
Zn	22.17	.339	.339		
Mn	0.8	.015	.015		
SiO ₂	0.6				
<hr/>					
	100.52				

In the specimen yielding this analysis, the sphalerite was visible as abundant grains of dark brown color. It was concluded that the zinc, manganese, and a small portion of the iron were derived from the sphalerite and calculation on this basis shows 40 per cent. of the latter to be present. Deducting this and neglecting the silica as unessential the figures of the last column are obtained which yield very closely the bornite formula Cu_5FeS_4 .

CAHNITE. This mineral, first described² a year ago in the form of crystals of minute to microscopic size, was found during the past summer in a small pocket in what may fairly be called gigantic crystals for this substance. The pocket was in 229 pillar, 20' from the 700 level north, near where Mr. Stanton first found cahnite in a rhodonite vein. The crystals were implanted on rhodonite and numbered in all about a dozen. They range in size from 2 cm. (about 3/4 inch) square, downward, are all twinned in the habit previously described for the mineral and present no new forms as they have been etched and slightly rounded. Plate IV, figures 4a and 4b, shows a typical specimen in photograph and drawing.

I am indebted to Mr. Bauer for the opportunity of securing these remarkable crystals and to Mr. Lewis for photographing and measuring them.

CLINOHEDRITE. Clinohedrite was first described in 1898 by Penfield and Foote³ and nothing has been added to their description of this interesting mineral in the ensuing thirty years. The material which they described came from the dump of the Parker Shaft and the mineral was not found in place at that time. The recent discovery of clinohedrite by Mr. Bauer in association with

² *Am. Mineral.*, 12, 149, 1927. In the figure in this paper showing cahnite, the letter *b*, wherever it appears should be changed to *a*.

³ *Am. Jour. Sci.*, 5, 289, 1898.

the two new lead silicates larsenite and calcium-larsenite⁴ seems a fitting occasion therefore to publish such new facts as have come to the writer's notice concerning it. These facts include new crystallographic data and two new analyses by Mr. Bauer, which serve to confirm the correctness of the original description.

As no table of position-angles for clinohedrite has been published these values are presented in TABLE I. The table includes the forms found by Penfield and a number since observed, marked with an asterisk, the data for which are contained in TABLE II.

TABLE I. ANGLE TABLE OF CLINOHEDRITE

$$a:b:c = .6824:1:.3226 \quad \beta = 103^{\circ}56'$$

$$p_0 = .4726 \quad q_0 = .3131 \quad \mu = 76^{\circ}04'$$

	ϕ	ρ		ϕ	ρ
* <i>a</i> (100)	90°00'	90°00'	<i>r</i> ($\bar{3}$ 31)	-51°24'	57°12'
<i>b</i> (010)	0 00	90 00	<i>s</i> ($\bar{5}$ 51)	-53 35	69 48
* <i>f</i> (210)	71 40	90 00	<i>t</i> ($\bar{7}$ 71)	-54 27	75 34
<i>h</i> (320)	66 10	90 00	* <i>k</i> ($\bar{3}$ 11)	-75 06	51 27
<i>m</i> (110)	56 29	90 00	* <i>k</i> ₁ (31 $\bar{1}$)	-75 06	51 27
<i>m</i> ₁ ($\bar{1}$ 10)	-56 29	90 00	* <i>A</i> (31 $\bar{1}$)	79 18	60 06
<i>n</i> (120)	37 02	90 00	* <i>g</i> ($\bar{5}$ 11)	-81 36	65 39
* <i>n</i> ₁ ($\bar{1}$ 20)	-37 02	90 00	<i>u</i> ($\bar{5}$ 31)	-66 07	67 18
<i>l</i> (130)	26 42	90 00	* <i>j</i> (25 $\bar{1}$)	-24 13	60 31
* <i>d</i> (150)	16 48	90 00	* <i>v</i> ($\bar{1}$ 71)	- 6 02	66 14
<i>e</i> (101)	90 00	36 19	* <i>w</i> ($\bar{1}$ 51)	- 8 25	58 29
<i>e</i> ₁ ($\bar{1}$ 0 $\bar{1}$)	90 00	36 19	* <i>x</i> ₁ (131)	37 13	50 33
<i>p</i> (111)	66 18	38 45	<i>x</i> ($\bar{1}$ 31)	37 13	50 33
<i>p</i> ₁ ($\bar{1}$ 1 $\bar{1}$)	66 18	38 45	<i>o</i> ($\bar{1}$ 31)	-13 52	44 54
<i>q</i> (111)	-36 31	21 52	<i>o</i> ₁ (13 $\bar{1}$)	-13 52	44 54
<i>q</i> ₁ (11 $\bar{1}$)	-36 31	21 52	<i>v</i> ($\bar{1}$ 2 $\bar{1}$)	48 43	44 22

From time to time crystals of clinohedrite, probably from the original locality, have come into the writer's hands which yielded the combinations of forms shown in Plate V, figures 5, 6, and 7. Two other specimens in which hodgkinsonite was associated with clinohedrite contained measurable crystals of the latter which are shown in Plate V, figures 8 and 9. These are probably from a second occurrence but its location in the mine is unknown. In 1928 specimens were found in the mine at Franklin on the 400 level in the north end which contained clinohedrite associated with a number of other species including larsenite as mentioned above. The clinohedrite is fairly abundant in clusters of prismatic crystals lining cavities and intergrown with needles of larsenite. It is

⁴ This number, page 334.

EXPLANATION OF PLATE V

Fig. 5. Clinohedrite crystal showing $a(100)$, $b(010)$, $h(320)$, $m(110)$, $m_1(\bar{1}10)$, $n(120)$, $l(130)$, $p(111)$, and $u(\bar{5}31)$.

Fig. 6. Clinohedrite. Projection on $b(010)$ of a crystal showing $b(010)$, $m(110)$, $m_1(\bar{1}10)$, $l(130)$, $d(150)$, $e(101)$, $p(111)$, $q(\bar{1}11)$, $r(\bar{3}31)$, $s(\bar{5}51)$, $t(\bar{7}71)$, $u(\bar{5}31)$, $k(\bar{3}11)$, $v(\bar{1}71)$, and $w(\bar{1}51)$.

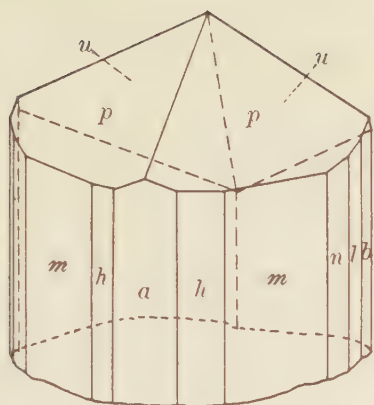
Fig. 7. Clinohedrite. Projection on $b(010)$ of a doubly terminated crystal showing $b(010)$, $m(110)$, $e(101)$, $e_1(\bar{1}0\bar{1})$, $p(111)$, $q(\bar{1}11)$, $q_1(11\bar{1})$, $o(\bar{1}31)$, $o_1(13\bar{1})$, $r(\bar{3}31)$, $s(\bar{5}51)$, $t(\bar{7}71)$, $u(\bar{5}31)$, $g(\bar{5}11)$ and $x(\bar{1}3\bar{1})$.

Fig. 8. Clinohedrite crystal showing $b(010)$, $m(110)$, $m_1(\bar{1}10)$, $e(101)$, $p(111)$, and $u(\bar{5}31)$.

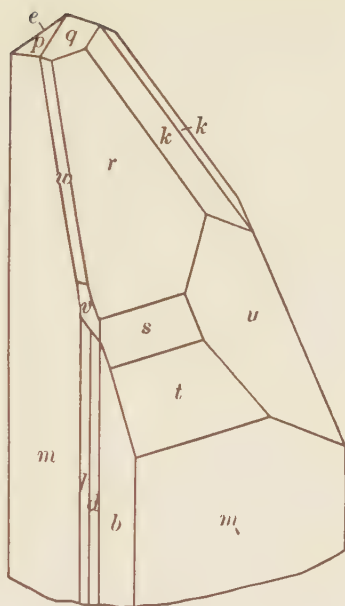
Fig. 9. Clinohedrite. Projection on $b(010)$ of a crystal showing $b(010)$, $m(110)$, $e(101)$, $p(111)$, $q_1(11\bar{1})$, $k_1(31\bar{1})$, $x(\bar{1}3\bar{1})$, and $j(25\bar{1})$.

Fig. 10. Clinohedrite. Projection on $b(010)$ of a crystal showing $b(010)$, $m_1(\bar{1}10)$, $n_1(\bar{1}20)$, $e(101)$, $p(111)$, $p_1(\bar{1}1\bar{1})$, and $A(\bar{3}1\bar{1})$.

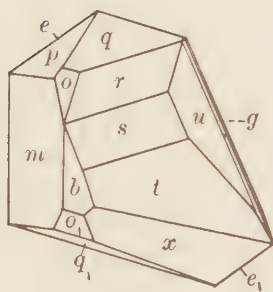
Fig. 11. Clinohedrite. Projection on $b(010)$ of a crystal showing $b(010)$, $m_1(\bar{1}10)$, $n_1(\bar{1}20)$, $e(101)$, $p(111)$, $p_1(\bar{1}1\bar{1})$, $q(\bar{1}11)$, $t(\bar{7}71)$, and $A(\bar{3}1\bar{1})$.



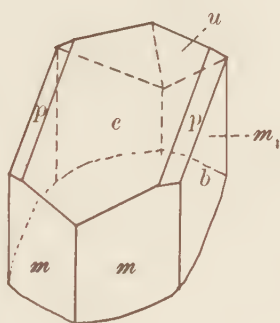
5



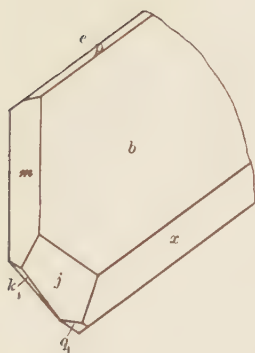
6



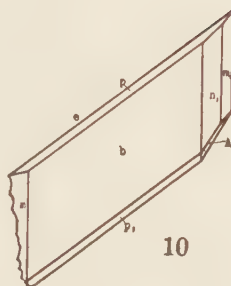
7



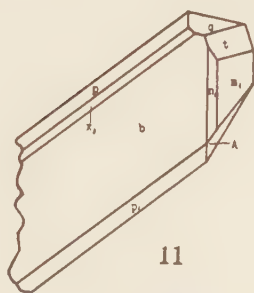
8



9



10



11

PLATE V

snow-white or glassy, transparent, with optical properties identical with those of the first described occurrence. The prismatic habit is developed parallel to the zone $[\bar{1}01]$ containing the forms e , p , b and p_1 . These crystals are shown in Plate V, figures 10 and 11, and are markedly different in appearance from any hitherto described. All the new forms were found on the above crystals, the measurements obtained constituting TABLE II. The angles measured both on these and on the known forms conform closely to those calculated from Penfield's axes.

TABLE II. DATA FOR NEW FORMS ON CLINOHEDRITE

	ϕ	ρ	
$a(100)$	$89^{\circ}39'$	$90^{\circ}00'$	Two narrow faces
$f(210)$	71 19	90 00	" " "
$n_1(120)$	-37 08	90 00	Five excellent faces
$d(150)$	16 39	90 00	One narrow face
$k(\bar{3}11)$	-75 04	51 24	Two distinct faces
$k_1(31\bar{1})$	-75 00	50 35	One poor face
$A(\bar{3}1\bar{1})$	79 13	59 55	Seven excellent faces
$j(25\bar{1})$	$-24^{\circ}51'$	$60^{\circ}27'$	Three good faces
$g(\bar{5}11)$	-81 37	65 48	Two poor faces
$v(\bar{1}71)$	- 5 48	66 20	Two fair faces
$w(\bar{1}51)$	- 7 50	58 11	One fair face
$x_1(131)$	36 33	50 08	Two poor faces

CHEMICAL ANALYSES OF CLINOHEDRITE

1. Analysis by Foote, 1898, average of two, Parker Shaft.
2. Analysis by Bauer, 1925, Parker Shaft.
3. Analysis by Bauer, 1928, Franklin, 400 level.
4. Number 3 recalculated to 100 per cent. after deduction of 5.42 per cent. calcite (including MnO, MgO, and FeO) equivalent to CO₂ found; and of 3.74 per cent. of larsenite equivalent to PbO found.

	1	2	3	4
SiO ₂	27.22	26.73	25.71	27.39
ZnO	37.44	37.13	34.55	36.78
CaO	26.25	26.25	27.62	27.41
MnO	0.50	1.11	0.29	.....
MgO	0.07	.....	0.36	.....
FeO	.....	.....	0.08	.....
H ₂ O	8.56	8.09	7.63	8.42
PbO	.....	.....	1.06	.....
CO ₂	.....	.....	2.48	.....
(Fe, Al) ₂ O ₃	0.28	0.37	0.30	.....
	100.32	99.68	100.08	100.00

Mr. Bauer analyzed a small sample (.183 gram) of the new-found clinohedrite which had been purified as completely as possible by Mr. Berman. It was impossible to free it entirely from larsenite and calcite. It is shown together with a second analysis of material from the Parker Shaft in the table below. They are essentially identical and yield the original formula, $H_2CaZnSiO_6$.

The rediscovery of clinohedrite in the mine at Franklin leaves only one of the numerous species described by Penfield from the Parker Shaft dump to be found again, namely nasonite. Roebbingite occurs in small amount with the new find of clinohedrite.

CLINOZOISITE. This mineral, not before described from Franklin, was identified by crystal form and optical characters among the many minerals coating the walls of the cavities from which gageite was first described. The principal wall coating is orange colored zincite upon which rest pyrochroite, willemite needles, gageite and calcite. The clinozoisite is in flattened prisms, deeply striated in the direction of their length and terminated by a single pair of pyramid faces with the angles and in the familiar habit of epidote. They are white to pale yellow in color and show basal cleavage.

Three crystals were measured, yielding poor reflections but sufficient to identify their forms according to the following table of angles.

	Measured		Calculated (for epidote, projection on 010).	
	ϕ	ρ	ϕ	ρ
$c(001)$	64°48'	90°00'	64°36'	90°00'
$a(100)$	0 00	90 00	0 00	90 00
$r(\bar{1}01)$	51 29	90 00	51 42	90 00
$f(\bar{3}01)$	-16 21	90 00	-16 46	90 00
$i(\bar{1}02)$	80 06	90 00	81 03	90 00
$n(\bar{1}11)$	-51 40	34 34	-51 42	35 13

Since the angles of epidote and clinozoisite are practically identical, the identification of these crystals as belonging to the latter species rests on their optical properties which were determined by Mr. Berman as follows:

Biaxial negative. Extinction parallel on length sections. $Z \wedge c = 31^\circ$. $Y = B$, $X = a$. Dispersion strong, $\rho > \nu$, $\alpha = 1.684$; $\beta = 1.691$; $\gamma = 1.698$.

These characters show the mineral to be closely related to clinozoisite but the indices are lower than those of any member of the zoisite group, even the newly described pumpellyite. As there

is no possibility of obtaining sufficient amounts of the mineral for chemical analysis, its true place in the series must remain uncertain.

CROCIDOLITE. Crocidolite has long been known from Franklin in inconspicuous narrow calcite veins in which it was associated with granular sphalerite. Recently it was found in abundance and the Stanton Collection contained numerous specimens showing its association. It is a very pale blue variety in excessively fine needles more or less felted together or contained as inclusions in other minerals. It appears to have formed vein-like masses in which the chief mineral is calcite in perfectly colorless anhedral, the exterior rounded and coated with crocidolite. Willemite is also found in similar rounded crystals of considerable size, pale green or perfectly colorless, but sometimes blue from included needles of crocidolite. Sphalerite too is found in these veins in paly green to white cleavage masses. The occurrence of needle-like crystals of quartz in one specimen is described on a later page of this paper.

A sample of crocidolite was analyzed by Mr. Bauer, as shown below in Column 1. The sample showed the presence of willemite by its fluorescence so the ZnO was deducted as Zn_2SiO_4 willemite (8.91 per cent.) and the analysis recalculated to 100 per cent. The specific gravity of this sample is 3.195.

	1	2	Molecular Ratios	
SiO_2	53.61	56.17	.936	936 = 20×47
Fe_2O_3	18.45	20.24	.126	150 = 3×50
Al_2O_3	2.23	2.45	.024	
FeO	2.16	2.38	.033	288 = 6×48
CaO	0.24	0.26	.005	
MnO	absent	.....	
MgO	9.11	9.99	.250	86 = 2×43
ZnO	6.50	.....	
Na_2O	4.86	5.33	.086	
Loss on ignition	2.90	3.18	.177	177 = 4×44
	100.00	100.00		

The formula may then be written, ignoring insignificant amounts of CaO and Al_2O_3 as: $4\text{H}_2\text{O} \cdot 2\text{Na}_2\text{O} \cdot 6(\text{Mg}, \text{Fe})\text{O} \cdot 3\text{Fe}_2\text{O}_3 \cdot 20\text{SiO}_2$.

Dr. M. A. Peacock, who has recently studied the chemical composition of the South African crocidolites⁵ has kindly discussed

⁵ This number, p. 258.

this analysis along similar lines and reports as follows: "Crocidolite may be regarded as containing the following molecules in varying proportions:

<i>l</i>	$(\text{Fe,Al})_2\text{O}_3 \cdot \text{H}_2\text{O} \cdot \text{SiO}_2$	(Penfield Molecule),
<i>m</i>	$(\text{Fe,Al})_2\text{O}_3 \cdot \text{H}_2\text{O} \cdot 4\text{SiO}_2$	(Gordon's ideal riebeckite molecule),
<i>n</i>	$(\text{H}_2,\text{Na}_2,\text{Ca},\text{Mg},\text{Fe})\text{O} \cdot \text{SiO}_2$	(Metasilicate amphibole molecule).

In the Franklin crocidolite *l* is small and *m* and *n* about equal in amount. It differs from South African crocidolite in having MgO greatly preponderating over FeO instead of the reverse, and in having a greater relative amount of Fe_2O_3 ."

GAGEITE. The existence of gageite as a definite mineral species rests upon an analysis made upon a very minute amount of material (.04 gr.). In a recent paper,⁶ Gordon has tried indeed to show that gageite was probably identical with tephroite. The following facts regarding this mineral seem, however, to establish its validity as an independent species.

The optical characters determined by Larsen on type material have been found to be characteristic of numerous specimens of the mineral leaving no ambiguity in its determination. In order better to establish its chemical nature, a gram sample of gageite was purified by Mr. Berman from a nearly homogeneous specimen obtained by the kindness of Captain George Rowe of Franklin and this was analyzed by Mr. Bauer.

1. Analysis of gageite by L. H. Bauer				
2. Analysis of gageite by R. B. Gage ⁷				
	1	Molecular Ratios		2
SiO ₂	23.58	.391	= 3 × .130	24.71
MnO	53.74	.758	} 1.054 = 8 × .132	50.19
MgO	9.95	.247		11.91
ZnO	3.96	.049		8.86
FeO	0.03			
Al ₂ O ₃	0.15			
H ₂ O	8.24	4.57	= 3 × .152	4.43(diff.)
	99.65			100.00

The composition is expressed by the formula $8(\text{Mn,Mg,Zn})\text{O} \cdot 3\text{SiO}_2 \cdot 3\text{H}_2\text{O}$. Specific gravity 3.584 (Pycnometer, Berman).

⁶ Gordon, S. G., *Proc. Acad. Sci. Phil.*, 79, 207, 1927.

⁷ *Am. Jour. Sci.*, 30, 283, 1910.

These results agree substantially with those originally obtained by Phillips, except for a somewhat larger content of water, and lead to the same formula as proposed by that author. In the Stanton Collection, there are many specimens in which gageite is associated with chlorophoenicite. No crystals were measurable. The gageite here as usual is in fibrous aggregates of pale pinkish tint and seems to be a replacement or pseudomorph after an unidentified mineral. A comparison of the chemical and optical characters of gageite with those of tephroite shows a wide divergence of nature. It would have to be compared rather to a "hydrotephroite" which is a vague name attached to various uncertain and indefinite alteration products of tephroite. There seems to the writer no good reason for denying the right of gageite to a definite place among the minerals.

GLAUCOCHROITE. This mineral was established by Penfield and Warren in 1899, on material found during the sinking of the Parker Shaft and has not since been identified at Franklin. The discovery and analysis of new material of this mineral is, therefore, a welcome contribution to our knowledge of it. Mr. Bauer has sent to the writer several specimens of bluish glaucochroite in massive form intermixed with willemite, hardystonite, tephroite and franklinite which were found on the picking table. Their place in the mine is unknown except that they came from a deep level.

Some of this material was purified by Berman and gave the following optical properties. Biaxial negative. $2V$ medium large. $\alpha = 1.68$, $\beta = 1.71$, $\gamma = 1.725$.

This sample was analyzed by Mr. Bauer as shown below. The powder gave under the iron spark-gap the willemite phosphorescence from isolated grains. The zinc found in the analysis was therefore calculated as willemite and deducted. The analysis is practically identical with the original analysis by Warren.

1. Analysis of glaucochroite by L. H. Bauer.
2. Analysis of glaucochroite corrected by deducting 3.29 per cent. willemite and recalculated to 100 per cent.
3. Analysis of glaucochroite by C. H. Warren, 1899.

	1	2	3
	Percentages	Percentages	Percentages
SiO ₂	31.72	31.92	31.48
MnO	33.13	34.30	38.00
CaO	29.04	30.06	28.95
MgO	2.23	2.31	
ZnO	2.40	.....
FeO	0.11	0.11	
PbO	0.31	0.32	1.74
Al ₂ O ₃	0.95	0.98	
	<hr/> 99.89	<hr/> 100.00	<hr/> 99.89

HETAEROLITE. This mineral was originally found in abundance at Sterling Hill in oxidized material and was first described by Moore in 1877, somewhat doubtfully as a zinc hausmannite. No further examination of the mineral was made until 1910 when the writer published a new analysis by Schaller and concluded that it was zinc hausmannite but in so doing ignored a considerable content of water which was not accounted for. In 1913, Ford and Bradley described hetaerolite from Leadville, Colorado, where also it was found amidst oxidized ores. They concluded that it should be regarded as a hydrous oxide with the formula $2\text{ZnO} \cdot 2\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$. But their material was impure and to obtain this result 10 per cent. of calamine had to be deducted from the analysis.

Mr. Bauer has now supplied analyses of a new occurrence of the mineral at Sterling Hill in which it is associated with unoxidized franklinite. These show scarcely a trace of water and yield an ideal ratio for zinc hausmannite, $\text{ZnO} \cdot \text{Mn}_2\text{O}_3$. This material is black and crystalline and identical with crystals from Franklin, long since measured by the author, which showed form and twinning similar to but not identical with those of hausmannite. Mr. Berman has compared the optical properties of the analyzed mineral with those of the measured crystals and of the type, massive mineral and finds them all so nearly alike that there now seems no reason to doubt that hetaerolite is a zinc hausmannite.

The following data establish the characters of unaltered hetaerolite. For the partly hydrated mineral hitherto described, the name hydrohetaerolite may well be employed.

The crystals from Franklin were first brought to the Harvard Mineralogical Laboratory by Mr. Cahn in 1914. They are minute black octahedroids lining druses in thin veins in massive ore, associated with jeffersonite, wine colored and pink hodgkinsonite and green willemite. Calcite sometimes fills the center of the vein. The crystals show only the unit pyramid (111) and base (001), the latter sometimes large. A few of them show the twinning illustrated in Plate VI, figures 12a and b, with four individuals in twin relation to a fifth on $e(101)$. There is, however, generally wide departure from the ideal symmetry here shown; some individuals may be smaller than others or quite lacking. The crystals, though brilliant, are somewhat faceted so that measurements were not satisfactory. On one simple crystal, however, four identical readings were obtained for the inclination of the pyramid to the base.

	ϕ	ρ	
Hetaerolite (111)	45°00'	57°55'	
whence $p_0 = c = 1.128$			
Hausmannite (111)	45°00'	58°32'	(Flink)
$p_0 = c = 1.157$			

The crystals from Sterling Hill are unmodified pyramids implanted on massive franklinite and show no twinning.

The color of hetaerolite is shining black with a dark brown streak. The table gives in comparative form the optical characters, observed specific gravity and calculated specific gravity (Gladstone and Dale) for the minerals of this group. The last named values are a measure of the effect produced by the introduction of water in the hetaerolite molecule.

TABLE I

	ω	ϵ	Sp. Gr.	Calculated Sp. Gr.
Hausmannite	2.46	2.15	4.86	
Zn-Hausmannite=Hetaerolite (Sterling Hill)	2.35	2.10	4.85	4.810
Hydrohetaerolite Colorado	2.26	2.10	4.55	4.537

The analysis by L. H. Bauer of a sample of hetaerolite from Sterling Hill, purified by Berman (Sp. gr. 4.85) is as follows:

	Percentages
Mn ₂ O ₃	64.21
Fe ₂ O ₃	0.24
ZnO	32.46
MnO	1.86
MgO	0.49
SiO ₂	0.18
H ₂ O	0.19
	<hr/>
	99.63

This analysis is that of an anhydrous oxide and it yields the ratio demanded by the formula ZnO · Mn₂O₃ with great exactness.

Hetaerolite is unaltered in the blowpipe and yields a zinc coating when reduced with soda on charcoal.

HODGKINSONITE. Hodgkinsonite has been found in recent years in a great variety of associations at Franklin and must be ranked as one of the most characteristic members of the mineral assemblage filling the "pneumotectic veins." Mr. Bauer has made two analyses which confirm the original chemical interpretation of this mineral. Its optical orientation has been more exactly fixed by Mr. Berman's studies. And Berman and Lewis have measured a number of crystals found among the abundant material of the Stanton Collection which considerably enlarges the crystallographic interest of the species. These crystals, instead of presenting a prismatic habit parallel to the *c* axis which has been hitherto the rule, are dominantly developed parallel to the *a* axis. Some are tabular parallel to the base (001) with strong development of the clinodome zone; others have neither base nor prisms except as line faces and the clinodomes determine the prismatic habit. In addition to these novel habits these crystals have yielded some 17 new forms additional to the 24 already established, making the form series a highly complex one.

The optical characters as revised by Berman are as follows:

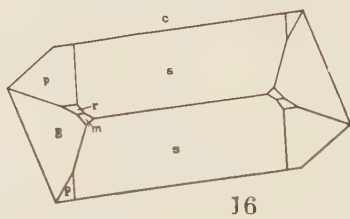
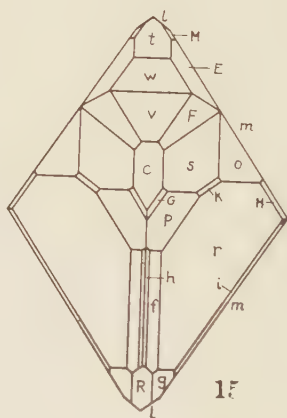
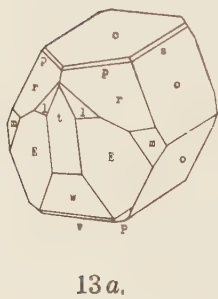
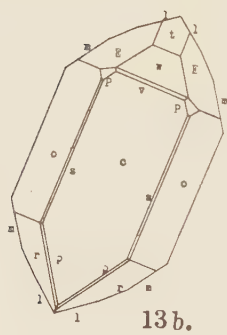
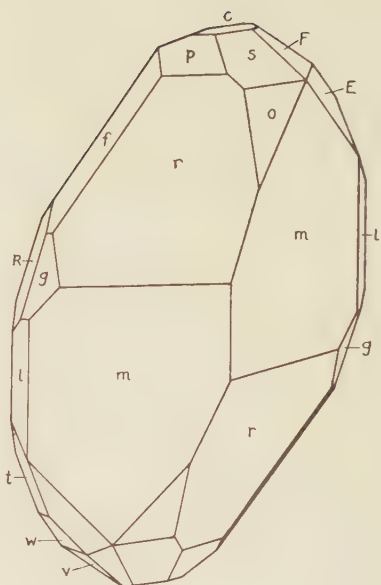
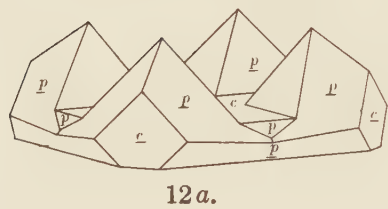
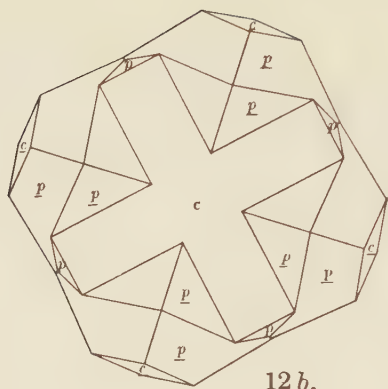
Biaxial negative, $2V = 50^\circ$ to 60°

$Y = b$, $Z \wedge c = 38^\circ$ Axial plane = (010)

$\alpha = 1.724$ = lavender

$\beta = 1.742$ = almost colorless

$\gamma = 1.746$ = lavender



EXPLANATION OF PLATE VI

Figs. 12a and b. Hetaerolite. Plan and clinographic projection of a twin group of five crystals showing the forms $c(001)$ and $p(111)$, four of the individuals twinned to the fifth one on faces of the second order pyramid.

Figs. 13a and b. Hodgkinsonite. Clinographic and basal projections of a crystal showing the forms $c(001)$, $m(110)$, $l(210)$, $s(011)$, $o(021)$, $v(\bar{4}03)$, $w(\bar{2}01)$, $t(\bar{4}01)$, $r(221)$, $E(\bar{4}21)$, $p(111)$, $P(\bar{1}11)$.

Fig. 14. Hodgkinsonite. Clinographic drawing with the axis b to the front, showing the forms $c(001)$, $m(110)$, $l(210)$, $s(011)$, $o(021)$, $v(\bar{4}03)$, $w(\bar{2}01)$, $t(\bar{4}01)$, $R(401)$, $r(221)$, $p(111)$, $f(211)$, $g(421)$, $F(\bar{2}23)$, $E(\bar{4}21)$.

Fig. 15. Hodgkinsonite. Basal projection of a crystal showing the forms of figure 14 with the addition of the forms $h(623)$, $i(441)$, $k(243)$, $G(223)$, $H(131)$, $M(\bar{6}21)$.

Fig. 16. Hodgkinsonite. A crystal projected on $b(010)$, showing the forms $c(001)$, $m(110)$, $s(011)$, $p(111)$, $P(\bar{1}11)$, $e(\bar{4}21)$.

In part of the vein yielding the willemite specimens described in a later part of this paper, the willemite crystals grow fewer or are wholly lacking. Their place is taken by scattered, implanted crystals of hodgkinsonite; bluish green tephroite crystals with tips blackened by oxide of manganese; and white barite crystals or platy masses, which, with calcite, sometimes wholly filled the fissure. The barite crystals and those of tephroite are of common habits but the hodgkinsonite presents a combination of forms wholly new to this mineral. The crystals are in part clear pink, in part of a fine topaz yellow color and do not exceed 5 mm. in diameter. Figure 13 shows the habit of the crystals; in contrast to all previous finds of hodgkinsonite the prism is almost lacking and the clinodome zone is dominant with o (021) and c (001) the principal faces.* The pyramids r (221) and E ($\bar{4}21$) are largely developed, the negative orthodomes v ($\bar{4}03$) w ($\bar{2}01$), and t (401) are prominent, the other forms present mainly as minute faces being as follows:

$m(110)$	$p(111)$
* $U(320)$	$P(\bar{1}11)$
$l(210)$	* $T(11.5.1)$
$s(011)$	

The two forms marked with an asterisk are new and are established by the following measured angles:

	Measured		Calculated	
	ϕ	ρ	ϕ	ρ
$U(320)$, 3 line faces between l and m , on edge between r and E	44°50'	90°00'	44°25'	90°00'
$T(11.5.1)$ 4 distinct faces, not shown in drawing between, and in zone with, t and r .	54 53	84 12	55 29	84 09

Among the specimens from the Stanton Collection, one hodgkinsonite specimen is remarkable for excellent crystals highly faceted with new forms. Figure 14, Plate VI, illustrates a find of small gem-like doubly terminated pink crystals delicately attached to larger singly terminated crystals of the same habit. One end of a doubly terminated crystal illustrated in plan by figure 15, Plate VI, measuring only 2 mm. in its greatest diameter gave reflections on one end from 44 faces of 26 forms of which 15 belonged to forms new to the mineral. The crystals are elongated parallel to the c axis with m (110) and r (221) dominant and in approximately

equal development. Eight excellent crystals were measured and the new forms are well established. The following table summarized the observations establishing the new forms:

Form	Average Measured		Calculated		No. of of faces	Variations from mean, minutes		No. of crystals
	ϕ	ρ	ϕ	ρ		ϕ	ρ	
<i>f</i> (211)	54°19'	62°15'	54°19'	62°13'	16	+ 7 - 8	+ 8 - 5	8
<i>g</i> (421)	53 28	75 00	53 27	74 57	11	+ 6 - 6	+ 4 - 4	7
<i>h</i> (623)	64 27	59 39	64 24	59 40	6	+ 6 - 7	+16 -14	4
<i>i</i> (441)	34 01	79 35	34 00	79 24	4	+ 7 - 3	+ 5 - 5	2
<i>k</i> (243)	21 32	57 52	20 28	57 26	5	+13 - 6	+16 -17	4
<i>G</i> (223)	38 24	43 06	38 00	43 08	3	+11 - 3	+ 2 - 1	3
<i>H</i> (131)	13 56	73 50	13 50	73 42	1	.....	.....	1
<i>J</i> (423)	54 55	52 07	55 07	52 15	1	.....	.....	1
<i>F</i> (223)	27 38	39 48	27 41	39 49	10	+11 -10	+ 7 - 5	5
<i>Z</i> (211)	60 13	50 41	60 13	50 40	3	+ 5 - 5	+ 1 - 1	2
<i>L</i> (423)	49 40	47 42	47 33	48 45	1	.....	.....	1
<i>M</i> (621)	62 26	78 15	62 27	78 12	1	.....	.....	1
<i>N</i> (012)	9 56	29 17	9 43	29 20	2	+ 2 - 2	+ 5 - 4	1
<i>Q</i> (023)	7 37	36 31	7 19	36 40	1	.....	.....	1
<i>R</i> (401)	90 00	71 36	90 00	71 30	7	.....	+16 - 8	7

The other forms present and shown in the drawing are *c*(001), *m*(110), *l*(210), *s*(011), *o*(021), *v*(403), *w*(201), *t*(401), *p*(111), *r*(221), and *E*(421). Another Stanton crystal shown in Plate VI, figure 16, and noteworthy for the dominance of the clinodome had only the forms *c*(001), *m*(110), *S*(011), *p*(111), *r*(221), *P*(111), *E*(421).

LEUCOPHOENICITE. Little of importance has been added to the physical and chemical data relating to leucophoenicite since it was first described by Penfield and Warren⁸ excepting the optical constants contained in Larsen's Tables and the crystal elements and forms published by the author,⁹ and reproduced in Goldschmidt's Atlas der Krystallformen. The angle tables and drawings as here given were already prepared in 1910 but are now first published.

⁸ *Am. J. Sc.*, 8, 339, 1899.

⁹ *Am. J. Sc.*, 29, 177, 1910.

Leucophoenicite. Axial ratio: $a:b:c = 1.1045:1:2.3155$; $\beta = 76^{\circ}44'$.

Forms:

<i>c</i> (001)	<i>s</i> (120)	<i>r</i> (101)	<i>o</i> (011)	<i>n</i> (121)	<i>d</i> (123)
<i>b</i> (010)	<i>e</i> (101)	<i>i</i> (102)	<i>f</i> (012)	<i>u</i> (122)	<i>h</i> (123)
<i>a</i> (100)	<i>t</i> (102)	<i>y</i> (103)	<i>p</i> (111)	<i>j</i> (122)	<i>q</i> (124)
<i>m</i> (110)	<i>x</i> (103)	<i>z</i> (104)	<i>l</i> (121)	<i>k</i> (211)	

Combinations:—

- | | | |
|---|------------------------------|------------------|
| 1. <i>c, b, a, s, e, r, i, y, o, l, n.</i> | | Figure 17 |
| 2. <i>c, b, a, s, r, y, o, l.</i> | | |
| 3. <i>c, b, a, e, t, r, i, o, l, n, u, d, h.</i> | Twin. Projection on <i>b</i> | Figure 18 |
| 4. <i>b, s, t, r, l, n.</i> | | |
| 5. <i>c, b, e, r, t, o, l, d.</i> | | |
| 6. <i>c, b, m, s, x, r, i, y, o, f, d, q.</i> | | |
| 7. <i>c, b, o, l, n, d.</i> | | |
| 8. <i>b, o, l, n, d.</i> | | |
| 9. <i>c, a, e, x, r, i, z, u, k.</i> | | Figure 19, a & b |
| 10. <i>a, e, x, r, i, y, z, o, u, k.</i> | Twin. | |
| 11. <i>c, b, a, e, t, r, i, f, n, d, h, p.</i> | | |
| 12. <i>a, x, r, i, z, u, k.</i> | | |
| 13. <i>c, a, e, x, r, i, s, z, u, k.</i> | Twin. Projection on <i>b</i> | Figure 20 |
| 14. <i>c, b, a, i, y.</i> | Twin. | Figure 21 |
| 15. <i>c, b, a, m, s, e, r, i, y, u, q, p, j.</i> | | Figure 22, a & b |

HABIT. Commonly in isolated crystalline grains or massive granular. Crystals rare, generally of epidote habit, more or less elongated parallel to the *b* axis, with striated orthodome zone; but also tabular parallel to the orthopinacoid or an orthodome. Crystals generally minute and frequently twinned on the base, either in contact or interpenetrating and with numerous lamellae in parallel growth.

The crystallization of leucophoenicite is here first described in detail, Penfield, who established the species, being unable to determine on his material even the crystal system. The first crystals measured by the writer came from a specimen in the collection of Mr. Canfield who most kindly consented to sacrifice a part of it for the purpose. Some ten crystals, combinations numbers 1 to 8, and figures 17 and 18, Plate VII, proved measurable but many were fragmentary and none were of first class quality. The measurements were made on the two-circle goniometer, the crystals, owing to their peculiar habit, being mounted so that the orthodome zone was vertical with (010) as pole. The measurements and calculated angles together with the elements and symbols of the forms in this position are contained in TABLE I.

TABLE I
Measured and calculated angles of leucophoenicite, (010) as pole.
Elements $p_0 = 4437$, $q_0 = 9302$ $\mu = 76^\circ 44'$

	Calculated		Measured		Limits		ρ	
	ϕ	ρ	ϕ	ρ	ϕ	ρ		
<i>c</i> 100	76°44'	90°00'	76°32'	90°00'	76°03'–77°14'		5	fair
<i>b</i> 001	00 00	00 00	00 00	00 00			8	good
<i>a</i> 010	00 00	90 00	00 00	90 00			3	poor
<i>m</i> 011	00 00	42 56	00 00	43 10			1	poor
<i>s</i> 012	00 00	24 56	00 00	25 00		24 52–25 11	4	good
<i>e</i> 110	22 42	90 00	22 33	90 00	22 27–22 55		2	very poor
<i>t</i> 210	37 18	90 00	37 17	90 00	36 36–37 18		3	good
<i>x</i> 310	46 22	90 00	46 45	90 00			1	good
<i>r</i> 110	–27 32	90 00	–27 10	90 00	27 00–27 39		5	fair
<i>z</i> 210	–49 37	90 00	–49 44	90 00	48 46–51 47		5	poor
<i>y</i> 310	–64 15	90 00	–64 01	90 00	63 32–64 25		3	good
<i>z</i> 410	–73 09	90 00	–73 36	90 00	73 14–73 45		5	fair
<i>o</i> 101	76 44	23 55	76 51	23 50	76 42–77 13	23 47–23 58	8	good
<i>f</i> 201	76 44	41 36	76 44	41 23		41 19–41 26	2	good
<i>p</i> 111	–27 32	43 03	–27 30	43 45			1	very poor
<i>n</i> 112	–27 32	25 02	–27 33	25 04			5	good
<i>l</i> 112	22 42	29 13	22 40	29 17	27 03–27 57	24 57–25 16	3	fair
<i>u</i> 212	–49 56	29 26	–49 16	29 20	22 30–22 49	29 12–29 22	1	good
<i>d</i> 312	46 22	41 50	46 33	41 49	45 54–46 38	41 38–41 57	5	good
<i>h</i> 312	–64 15	35 44	–64 20	35 50	64 16–64 26	35 33–36 07	2	good
<i>q</i> 412	–73 09	42 04	–73 06	41 33			1	good
<i>j</i> 212	37 18	35 28	37 04	35 39			1	fair
<i>k</i> 121	–13 48	61 05	–13 21	61 29	12°10'–14°58'	59°45'–62°25'	9	very poor

In TABLE II may be found the elements and symbols transformed to the normal position with the calculated angles for the forms. The letters and order of listing serve to identify the corresponding forms in the two tables.

The calculation of the elements is based on the measurements given by 27 faces of 6 forms on 8 crystals, only those faces which gave sharp images on the goniometer being employed. The position chosen was that which gave the simplest symbols and at the same time brought the twin and cleavage plane into the position of basal pinacoid. No interpretation of the highly peculiar assemblage of forms offered the slightest resemblance to the form series of any member of the humite group to which leucophoenicite is related chemically.

TABLE II

Elements and calculated angles of leucophoenicite, normal position.

Elements $p_0 = 2.0965 \cdot q_0 = 2.2538 \quad \mu = 76^\circ 44'$.

	ϕ	ρ		ϕ	ρ
<i>c</i> 001	90°00'	13°16'	<i>o</i> 011	5°49'	66°45'
<i>b</i> 010	00 00	90 00	<i>f</i> 012	11 31	49 45
<i>a</i> 100	90 00	90 00	<i>p</i> $\bar{1}$ 11	-39 38	71 36
<i>m</i> 110	42 56	90 00	<i>n</i> $\bar{1}$ 21	-22 30	78 43
<i>s</i> 120	24 56	90 00	<i>l</i> 121	27 18	79 08
<i>e</i> 101	90 00	67 18	<i>u</i> $\bar{1}$ 22	-19 58	67 54
<i>t</i> 102	90 00	52 42	<i>d</i> 123	31 42	61 08
<i>x</i> 103	90 00	43 38	<i>h</i> $\bar{1}$ 23	-17 21	58 16
<i>r</i> $\bar{1}$ 01	-90 00	62 28	<i>q</i> $\bar{1}$ 24	-14 39	50 07
<i>i</i> $\bar{1}$ 02	-90 00	40 04	<i>j</i> 122	29 33	69 25
<i>y</i> $\bar{1}$ 03	-90 00	25 44	<i>k</i> $\bar{2}$ 11	-60 22	77 57
<i>s</i> $\bar{1}$ 04	-90 00	16 51			

Much has been learned since its original description of the occurrence of leucophoenicite in the mine at Franklin. It is now known to be a very common mineral there, constituting veins and replacement areas in the ore and has frequently been found in place. Two occurrences especially were observed and described to the author by Mr. Hodgkinson, formerly of the Mine staff at Franklin. One consists of a single small cavity in ore, an opening in a vein consisting of leucophoenicite and willemite in granular admixture. This cavity is lined with pale yellow drusy garnet upon the surface of which are implanted crystals of leucophoenicite and willemite and a single white calcite scalenohedron. The willemite is pale green, long prismatic in habit and brilliant in

lustre. The leucophoenicite is clear red in color in striking contrast to its background. The crystals are slender prismatic forms both simple and twinned, the longest doubly terminated, about one-third of an inch in length and showing the forms of Plate VII, figure 19. The twin shown in Plate VII, figure 20, and the combinations 10, 11, and 12 are from this specimen. These crystals have suffered somewhat from etching so that the measurements given were poor but they sufficed to establish the forms, characteristic for which are the orthodome z and the pyramids u and k .

Another occurrence of leucophoenicite was found by Mr. Hodgkinson in place in the northern end of the mine near the hanging wall of the west leg of the ore body, within two feet of a dike of pegmatite. It occurs in a continuous seam with swells and pinches, the former making vugs in which the crystals have formed. The specimens at hand show walls of banded ore with much franklinite which on the boundary of the cavity is in isolated cubic crystals. The walls of the central cavity are coated with gray calcite, merging inward to pale rhodochrosite, poorly crystallized in parallel groups of rhombohedra. Upon the carbonates is a coating of silky, felted sussexite, often in a thin film adhering closely. A central mass four inches or more across consists of massive, dull-brown leucophoenicite, becoming crystallized towards the center, either in the slender plate-like crystals shown in Plate VIII, figure 21, the broad surface deeply striated by twinning, with bright faces of the base or basal cleavage; or in rarer, isolated, stouter, more brilliant crystals like Plate VIII, figure 22. These are clear pink and of a lively color, the plates dull brown, clear to opaque. In some cases groups of the platy crystals are aggregated in fan-shaped groups, rising from the massive matrix.

These specimens have added much to our knowledge of the crystallography of leucophoenicite and are much the most attractive yet found of this peculiar mineral.

EXPLANATION OF PLATE VII

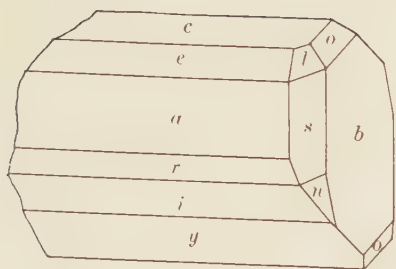
Fig. 17. Leucophoenicite. Crystal showing $c(001)$, $b(010)$, $a(100)$, $s(120)$, $e(101)$, $r(\bar{1}01)$, $i(\bar{1}02)$, $y(\bar{1}03)$, $o(011)$, $l(121)$, and $n(\bar{1}21)$.

Fig. 18. Leucophoenicite. Projection on b of interpenetrating twin crystals twinned on $c(001)$. A combination of $c(001)$, $b(010)$, $a(100)$, $e(101)$, $t(102)$, $r(\bar{1}01)$, $i(\bar{1}02)$, $o(011)$, $l(121)$, $n(\bar{1}21)$, $u(\bar{1}22)$, $d(123)$, and $k(\bar{1}23)$.

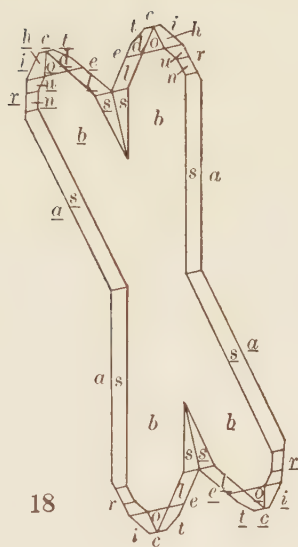
Fig. 19a. Leucophoenicite. Projection on b of a crystal showing $c(001)$, $a(100)$, $e(101)$, $x(103)$, $z(\bar{1}04)$, $i(\bar{1}02)$, $r(\bar{1}01)$, $u(\bar{1}22)$, and $k(\bar{2}11)$.

Fig. 19b. Leucophoenicite. The same crystal as shown in 19a in clinographic projection showing the prismatic development parallel to the b axis.

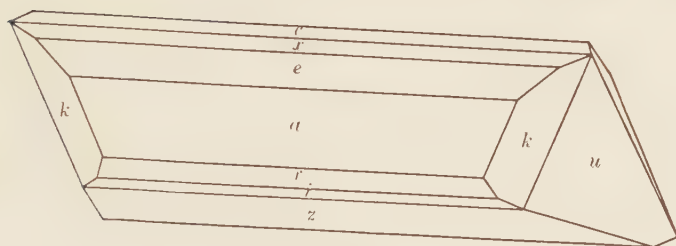
Fig. 20. Leucophoenicite. Projection on b of a crystal twinned on $c(001)$, showing $c(001)$, $a(100)$, $s(120)$, $e(101)$, $x(103)$, $r(\bar{1}01)$, $i(\bar{1}02)$, $y(\bar{1}03)$, $z(\bar{1}04)$, $u(\bar{1}22)$, and $k(\bar{2}11)$.



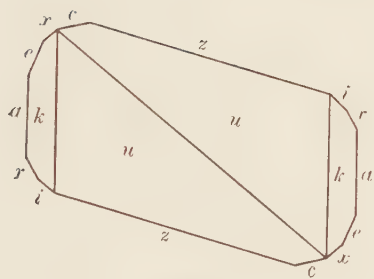
17



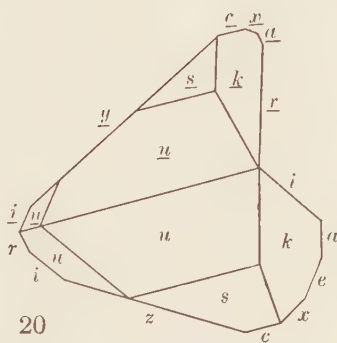
18



19 b.



19 a.



20

MANGANITE. The monohydrate of manganese has not previously been reported from Franklin. A specimen which proves to contain this mineral has been received from Mr. Bauer. It consists of a small fragment of compact limestone with a network of vugs lined with calcite crystals, some of which are very brilliant. Implanted on these are clusters of slender radiating needles, black and lustrous, which by chemical tests and crystal form proved to be manganite. The specimen was found in the mine at Sterling Hill but the exact locality is not given. Although the crystals are bright they are much striated and yielded poor measurements. These, however, sufficed to show the presence of the forms $a(100)$, $k(230)$ and $u(101)$. In another specimen loaned by the U. S. National Museum the manganite crystals line cavities in a massive yellow andradite garnet.

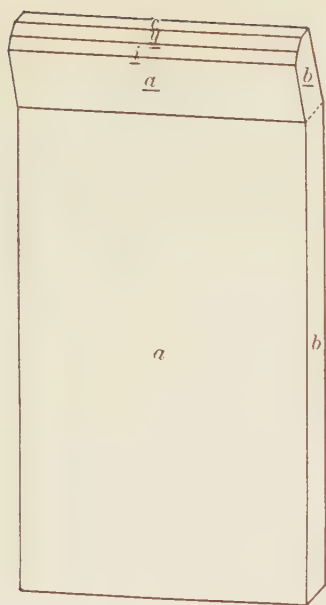
QUARTZ. Quartz has until recently been a mineral rather conspicuous at Franklin by its absence. Numerous specimens in the Stanton Collection, however, show it in veins in massive ore with wall surfaces coated with drusy crystals. And it is also found in cavities in carbonate veins in crystals of ordinary habit. It is, however, to call attention to a very peculiar specimen from Franklin presented to the Museum by Mr. Bauer that the mineral is here mentioned. This is a vein in ore, the walls of which are lined with rhombohedral calcite crystals on which are minute plates of hematite. The whole cavity of the vein is filled with a felted mass of the finest crocidolite fibre, pale blue in color; lying loose in the felt or slightly attached to the wall by one end are needles of quartz, colored faintly blue by inclusions of crocidolite. These needles range from minute spicules to slender rods 3 cm. long and 3 mm. in diameter. They are of trigonal cross section and represent extremely steep rhombohedrons, doubly terminated and without visible planes of the prism, much more like calcite forms than any quartz crystals known to the writer. The tip of the crystal may be needle-sharp; or it may be terminated by the faces of the positive and negative unit rhombohedrons. Although there are no visible prism faces and the crystal planes are dull, faint reflections were observed at 90° , the prism position, doubtless caused by minute striations. Readings were obtained from the rhombohedron faces only by wetting with alcohol or attaching glass slips with a film of liquid. The average reading obtained was $\rho = 87^\circ 30'$ which agrees most nearly with the form $Y(18.0.\overline{18.1})$,

EXPLANATION OF PLATE VIII

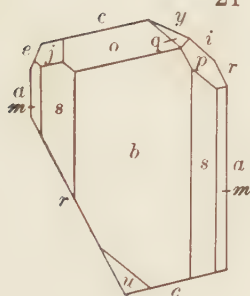
Fig. 21. Leucophoenicite. Unsymmetrical twin on $c(001)$. Showing on one half $a(100)$, and $b(010)$, and on the other half $a(100)$, $b(010)$, $c(001)$, $i(\bar{1}02)$, and $y(\bar{1}03)$.

Fig. 22a and b. Leucophoenicite. Projection on b and clinographic projection of a crystal showing $c(001)$, $b(010)$, $a(100)$, $m(110)$, $s(120)$, $e(101)$, $r(\bar{1}01)$, $i(\bar{1}02)$, $y(\bar{1}03)$, $u(\bar{1}22)$, $q(\bar{1}24)$, $p(\bar{1}11)$, and $j(122)$.

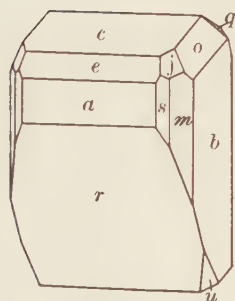
Fig. 23. Quartz. Drawing of a crystal showing the rhombohedrons $r(10\bar{1}1)$, $z(01\bar{1}1)$ and $Y(18.0.\bar{1}8.1)$.



21



22 a.



22 b.



23

$\rho = 87^{\circ}29'$. It might, however, equally well be compared with the form $\Omega(0.17.\bar{1}\bar{7}.1)$, $\rho = 87^{\circ}21'$. In the lack of evidence as to the positive or negative character of the rhombohedron, it was taken as Y and is so drawn in figure 23, Plate IX.

The only comparable quartz crystals which have been figured are shown by LaCroix¹⁰ from La Gardette.

SMITHSONITE. The carbonate of zinc has long been known both at Franklin and Sterling Hill in massive, earthy, or spheroidal forms. Measurable crystals, always rare in smithsonite, have not been found there until recently upon a specimen saved on the picking table at Franklin. Mr. Bauer sent this specimen to the Harvard Museum for determination. It is a fragment of coarse franklinite-willemite ore with two or three solution cavities some lined with needles of calamine and one with pure white crystals of smithsonite. The crystals are of typical calcite habit, the scalenohedron $v(2\bar{1}31)$ dominant with sometimes small faces of prism and rhombohedrons. The faces are brilliant and perfect, and give excellent position angles agreeing perfectly with those calculated from the accepted cleavage angle.

	ϕ	ρ
$v41$, $(2\bar{1}31)$ observed average of 6 faces	$10^{\circ}54' \pm 11'$	$67^{\circ}54' \pm 3'$
Calculated	$10^{\circ}53'$	$67^{\circ}54'$

Figure 24, Plate IX, shows the habit of the crystals.

So far as can be found by examination of the literature no scalenohedron has been measured or figured for smithsonite; while this form v is listed it must have been determined only by inspection. The material at hand is insufficient for analysis but its quality indicated great purity and invited optical study. Mr. Berman measured the indices and obtained results presented together with comparative data in the following table.

¹⁰ *Min. de la France et ses Col.*, 3, 86, 1901. Figure 56.

SMITHSONITE—OPTICAL DATA

(Immersion media used for determinations)

Harvard cat. number	Locality	Percentage ZnCO ₃	ω $\pm .002$	ϵ $\pm .003$	Sp. Gr.	
1.	Franklin, N. J.		1.850Na 1.845	1.625	4.43	clear colorless crystals.
2. 84307	Marion Co. Ark.	98.78	1.840Na			yellow— massive.
3, 84301	Kelly N. M.	93.92	1.847		4.410	blue—massive.
4.	Tsumeb S. W. Africa		1.848			clear colorless crystals to somewhat blue.
5. 84324	Broken Hill Rhodesia	97.34	1.8485	1.6212	4.398	colorless crystals.
6. 84326	Spain		1.840			brown botryoi- dal radiating fibers.
7.	Larium Greece		1.839			light blue.
8. 84328	Altenberg		1.847		4.00-4.20	brownish crystals.

1. Not analyzed. Crystal data above. Optical properties indicate that material is quite pure.

2. Analysis as given indicates almost pure material but the value for $\omega(\text{Na}) = 1.840$ is somewhat too low for material of that purity.

3. Contains CuO = 3.48 per cent.

4. Not analyzed material but probably pure.

5. Data from E. D. Mountain, *Min. Mag.*, 21, No. 113, p. 51, 1926.

6. Not analyzed.

7. Not analyzed.

8. Probably fairly pure ZnCO₃.

The foregoing table indicates that the optical properties of smithsonite are fairly constant for various compositions within a short range. Although the few figures given in textbooks and reference books on mineralogy vary markedly from the above given data, there seems to be no reason to suppose that such a variation exists. The highest value given for the refractive index

in the calcite group is that for siderite, $\omega = 1.875$ for pure FeCO_3 ; it seems, therefore, unlikely that the smithsonite from Moresnet, Belgium, should have for its index of refraction 1.872 as reported by Gaubert.¹¹ The optical constants given by Mountain, number 5 of the table, are probably very close to those for pure ZnCO_3 .

SUSSEXITE. This borate of manganese and magnesium is one of the minerals peculiar to Franklin. It has been found in a variety of associations at different times but never in large amounts. Recently there was found on the picking table a specimen so different in appearance from the normal sussexite that Mr. Bauer made an analysis which, with a specimen of the mineral, he has kindly placed at my disposition. It shows a narrow vein in massive ore largely composed of yellowish willemite with which is intermingled a dull pink massive substance looking somewhat like garnet, and some carbonate. The pink mineral is the sussexite; when crushed it shows under the microscope a felted fibrous structure quite unlike the ordinary parallel and separable-fibrous texture of sussexite. The optical data, however, and the analysis show it to be that mineral. In it, however, there is much less magnesium than in the type material and correspondingly more manganese. It is, therefore, quite a distinct facies of sussexite.

The optical characters were determined by Berman as follows:

Biaxial negative. 2V small, elongation negative, parallel extinction. $\alpha = 1.65$; $\beta = 1.71$; $\gamma = 1.715$.

1. Analysis of sussexite, Franklin, by L. H. Bauer.

2. Same recalculated to 100 per cent. after removal of 4.5 per cent. willemite shown to be present by phosphorescence.

3. Sussexite. Penfield & Sperry.

	1.	2.	3.
	Percentages	Percentages	Percentages
B_2O_3	29.20	30.52	33.31
MnO	47.27	49.40	38.08
MgO	9.15	9.56	15.92
ZnO	3.14	.....	3.24
CaO	1.94	2.03	.....
FeO	0.15	0.16	.....
SiO_2	1.30	.....	.....
H_2O	7.97	8.33	9.43
	-----	-----	-----
	100.12	100.00	99.98

* *Bull. de la Soc. Min. de France*, Vol. 42, 99, 1919.

EXPLANATION OF PLATE IX

Fig. 24. Smithsonite. Drawing of a crystal showing the forms $m(10\bar{1}0)$, $f(02\bar{2}1)$ and $v(21\bar{3}1)$.

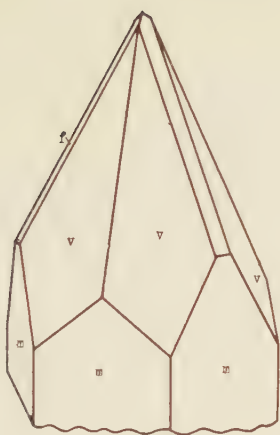
Fig. 25. Tephroite. Projection on $a(100)$ of a twin crystal, twinned on $h(011)$, showing the forms $a(100)$, $b(010)$, $m(110)$, $s(120)$, and $f(121)$.

Fig. 26. Willemite. Photograph of the crystal shown in the next figure.

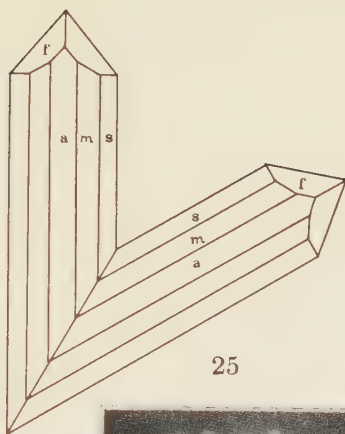
Fig. 27a. Willemite. Drawing of a crystal showing the forms $a(11\bar{2}0)$, $r(10\bar{1}1)$, $x(3\bar{1}21)$, $y(21\bar{3}1)$, and $k(4\bar{1}32)$.

Fig. 27b. Willemite. Plan of the crystal of figure 27a.

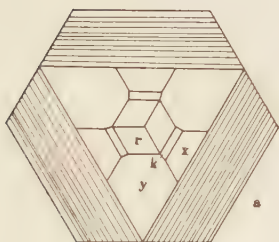
Fig. 28. Willemite. Plan of a crystal similar to figure 27a but more complex, showing the forms $a(11\bar{2}0)$, $s(11\bar{2}3)$, $f(4\bar{2}23)$, $e(01\bar{1}2)$, $g(01\bar{1}5)$, $r(10\bar{1}1)$, $k(4\bar{1}32)$, $x(3\bar{1}21)$, $y(21\bar{3}1)$, $d(12\bar{3}2)$, $D(\bar{1}322)$, and $q(13\bar{4}1)$.



24



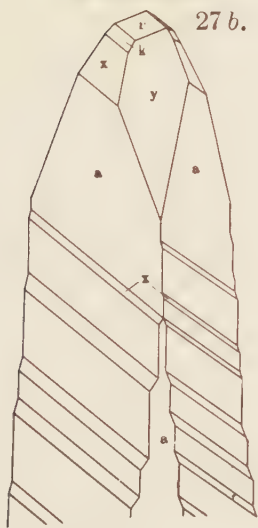
25



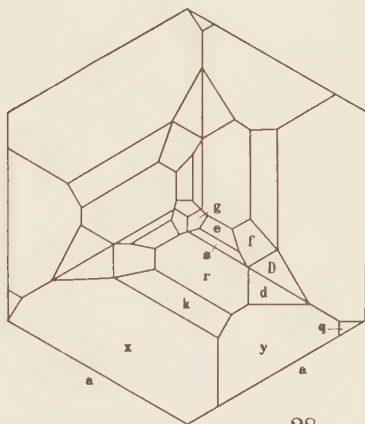
27 b.



26



27 a.



28

TENNANTITE. Mr. Bauer recently submitted for identification a specimen from the 900 level at Sterling Hill which he reported to contain copper, sulphur and arsenic. It proved to be an intimate intergrowth of three minerals, sphalerite, galena, and tennantite. The latter is in well developed crystals showing the forms *o*, *d* and *n* in about the proportions of figure 4, page 138, Dana's System. In another specimen from the same vein the crystals of tennantite are implanted on stilbite with which is an intimate network of crystals of actinolite, epidote, and barite. Thus still another species is added to the long and growing list of Franklin minerals.

TEPHROITE. Clear red or pink crystals of tephroite like those described and figured by Gordon in 1922,¹² were separated from the associated garnet and willemite and this sample was analyzed by Mr. Bauer, with the following result:

Analysis of Tephroite	
	Percentages
SiO ₂	29.13
MnO	66.81
MgO	0.46
ZnO	1.53
FeO	0.31
Al ₂ O ₃	1.48
H ₂ O	0.20

	99.92

The alumina is probably derived from a small amount of garnet in the sample. As it is the nearest to the pure Mn₂SiO₄ of any tephroite yet studied, its optical characters were determined by Berman. The specific gravity is 4.113 (pycnometer)

Biaxial (—), $2V = 60^\circ \pm$ $\rho > \nu$ perceptible
 $X = b$, $Z = c$
 $\alpha = 1.77$; $\beta = 1.807$; $\gamma = 1.825$ all $\pm .001$ for sodium light.

On a specimen of tephroite in Mr. Canfield's Collection two tiny crystals were marked as showing twinning. One of these was detached and on measurement proved to be twinned on a face of the dome *h*(011) which is also the twin plane in glaucochroite and chrysolite, other members of the same group of minerals. Figure 25, Plate IX, shows the simple contact twin, projected on the front

¹² *Proc. Acad. Nat. Sci. Phila.*, 74, 105, 1922.

pinacoid $a(100)$. The forms present are $a(100)$, $b(010)$, $m(110)$, $s(120)$, and $f(121)$. As the measurements were poor the determination of the twin plane was made graphically in projection on $a(100)$.

WILLEMITE. Willemite continues to be the most interesting constituent of the Franklin ores. There seems to be no end to the variety of its facies. Color varieties, textural varieties and crystal developments in ever varying habits are constantly appearing.

Specimens recently acquired by the Harvard Mineralogical Museum reveal an occurrence of willemite and other associated minerals so unusual that they seem worthy of a special note of description. These specimens clearly came from a vein cutting the massive ore which was open for at least a short space although probably hardly more than a crevice. Coating the vein wall is a crust of drusy yellow garnet; upon it are pink hodgkinsonite crystals of unusual habit; bluish tephroite crystals with tips blackened by manganese oxide; crystals of clear or snow-white barite; and a few minute deep red needles of what proves to be a vanadate, probably descloizite.

Most of the specimens from this vein are studded with willemite crystals of most unusual beauty. They are prisms of absolute transparency, colored a fine uranium green, and, considering their quality and complex crystallization, of unusual size, the largest measuring about 10 and 2 mm. in length and diameter. Their habit is dominated by a stepwise development of the third order rhombohedron $x(21\bar{3}1)$ in combination with the second order prism.

The combinations presented by the measured crystals with the number of faces of each form observed are contained in the following table:

Crystal	<i>a</i>	<i>c</i>	<i>r</i>	<i>s</i>	<i>e</i>	<i>x</i>	<i>y</i>	<i>D</i>	<i>d</i>	<i>k</i>	<i>q</i>	<i>f</i> *	<i>g</i> *	<i>G</i> *
I	6		3	3	3	3	3	3	3	2		3	1	
II	6		3	3	3	3	3	3	3	3		3		1
III	6	1	3	3	3	3	3	3		3	2	3	1	
IV	6		3			3	3	3	3	3				

* New forms.

Figure 26, Plate IX, shows in part the deeply striated appearance of these crystals.

So clear is the material that striations on the back of the crystal are plainly visible through its thickness. Some of them, attached by a prism face, are doubly terminated giving the effect of an enormously elongated rhombohedron. In Plate IX, figure 27a, the elongated rhombohedral aspect due to the oscillation between x and a is represented. As shown on the plan, Plate IX, figure 27b, the upper part of the crystal is bounded by three alternate faces of a . These step down with x and become smaller while the other three faces of a become larger and at the middle of the crystal the six faces of a are in equal development. The same thing occurs on the bottom between the under faces of x and alternate faces of a . Figure 28, Plate IX, shows in plan the distribution of faces as shown on the more highly modified crystals where the rhombohedral aspect is not pronounced.

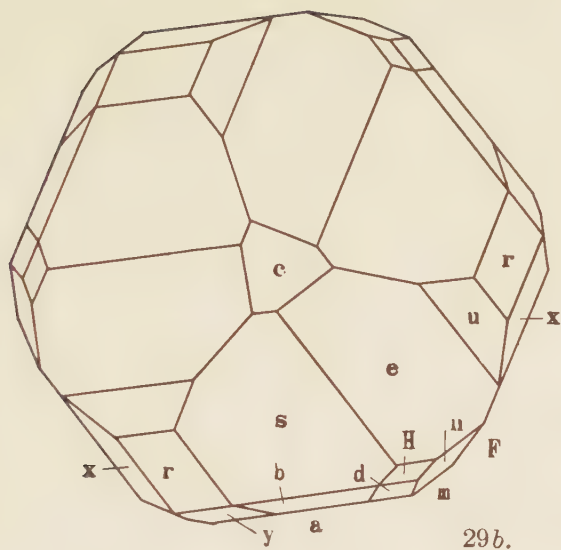
Among the many specimens of crystallized willemite acquired by the Harvard Museum with the Stanton Collection of Franklin minerals was one group distinguished by its extraordinary complexity of crystallization. The prism zone is rounded and vertically striated and the terminal forms are dominantly flat as shown in Plate X, figures 29a and 29b. The crystals are colorless to pale green and show the forms of the following list:

$c(0001)$	$r(10\bar{1}1)$	$b(22\bar{4}3)$
$a(11\bar{2}0)$	$s(11\bar{2}3)$	$d(12\bar{3}2)$
$m(10\bar{1}0)$	$e(01\bar{1}2)$	$*h(13\bar{4}4)$
$*F(31\bar{4}0)$	$u(2\bar{1}13)$	
$*(51\bar{6}0)$	$n(02\bar{2}1)$	* New forms
$*(21\bar{3}0)$	$x(3\bar{1}21)$	
$*(71\bar{8}0)$	$y(21\bar{3}1)$	

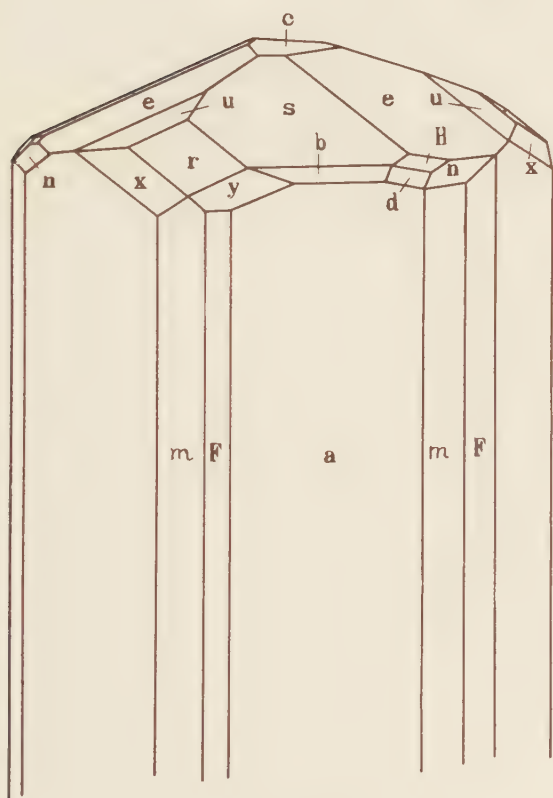
In the following table a summary of the observations made on the new forms is tabulated. The prisms were observed in the striated zone of the stout crystals, and, although they yielded definite signals, they are considered doubtful forms pending confirmation.

EXPLANATION OF PLATE X

Figs. 29a and b. Willemite. Clinographic and basal projections of a crystal showing the forms $c(0001)$, $a(11\bar{2}0)$, $m(10\bar{1}0)$, $F(31\bar{4}0)$, $s(11\bar{2}3)$, $u(2\bar{1}13)$, $b(22\bar{4}3)$, $r(10\bar{1}1)$, $e(01\bar{1}2)$, $n(02\bar{2}1)$, $x(3\bar{1}21)$, $y(21\bar{3}1)$, $d(12\bar{3}2)$, and $h(13\bar{4}4)$.



29b.



29a.

WILLEMITTE—NEW FORMS

Form	Average ϕ	Measured ρ	Calculated ϕ	Calculated ρ	No. of Observa- tions	Var. from mean ϕ	Var. from mean ρ	No. of cry- stals
<i>f</i> (4223)	0°02'	41°42'	0°00'	41°41'	9	+ 8 - 8	+1 -1	3
<i>H</i> (1344)	43 53	34 52	43 54	34 48	3	+ 3 - 2	0	
<i>G</i> (1765)	22 32	45 27	22 25	45 19	1	.....	.....	1
<i>g</i> (0115)	29 36	8 53	30 00	8 46	2	+39 -39	+5 -5	2
<i>F</i> (3140)	16 25	90 00	16 06	90 00	3	+25 -17	.....	2
(2130)	49 02	90 00	49 07	90 00	1	.....	.....	1
(7180)	23 11	90 00	23 25	90 00	2	+ 9 - 9	.....	1
(5160)	20 12	90 00	21 03	90 00	2	+28 -27	.....	1

MISCELLANEOUS. The following minerals have been definitely recognized on Franklin or Sterling Hill specimens and are to be added to the locality list:

Anhydrite—Franklin.
 Heulandite—Sterling Hill.
 Stilbite—Sterling Hill.
 Epistilbite—Sterling Hill.
 Gypsum—Franklin and Sterling Hill.

With these additions the author's list of minerals from these localities now numbers 128 definite species.

An explanation for the great abundance and variety of new facts obtained of recent years regarding the Franklin minerals lies chiefly in two circumstances. The active development to deep levels of the Sterling Hill mine has brought to light a host of new data. More important, however, than this is the watchful interest of the chemical staff of the New Jersey Zinc Company. Every new occurrence of minerals in the mines is noted, material secured and analyzed, and its mineralogical nature established. That this is a new state of affairs at Franklin will be apparent to all who have in earlier years been familiar with the local conditions.

The author desires to acknowledge his great indebtedness to the New Jersey Zinc Co. for permission to publish the many analyses made by their Franklin chemists.

THE PHOSPHORESCENCE AND FLUORESCENCE OF
FRANKLIN MINERALS

CHARLES PALACHE

The use of ultraviolet light as yielded by the iron-arc spark-gap to determine the presence of willemite in mill-tailings has long been an important practice at Franklin. From it has grown up the constant use of this apparatus in determining the presence in the Franklin ores not only of willemite but also of a number of other minerals which give characteristic reactions to this form of stimulus. Since these reactions may not be generally known it seemed desirable to give a brief account of the apparatus used and of the observations which may be made with it.

The spark-gap apparatus used in this laboratory is one made by the preparator, and modelled after the instrument manufactured for a short time by the General Electric Company and described by Mr. Andrews.¹

Mr. Littlefield has prepared the following brief description and figure showing its design. Figure 1 shows the electrical layout of the apparatus which consists of three major parts: the transformer, the condenser and the gap. It was possible to obtain a suitable transformer from a radio supply-house. The condenser was made by placing thin sheets of copper in alternate layers with old photographic plates from which the gelatin had been removed. Eight sheets of copper 6"×6" were found to give the desired capacity. The gap was made with one adjustable and one fixed electrode, being enclosed in a cup-shaped receptacle of insulating material. The electrodes were provided with removable tips of iron about 3/16" in diameter. It is installed in a box having a holder for the gap on the outside and provided with a snap-switch for making connection with the line (lighting circuit). The apparatus differs from that described by Mr. Andrews only in refinement of construction.

By the term fluorescence as here used is meant the color reaction given by some minerals when exposed to ultraviolet light. If this color endures after the light is extinguished the mineral is said to show phosphorescence. No observation of phosphorescence of very short duration is here included. The only Franklin mineral

¹ *General Electric Review*, Vol. XIX, No. 4, p. 317, 1916.

showing strong phosphorescence is willemite. It is well known that these phenomena are rarely given by pure materials but are caused by the presence of impurities of some sort generally in very small amounts. Hence these characters are variable in intensity and the same mineral may or may not react. Notwithstanding this variability, the characters are sufficiently well defined to be exceedingly useful both in determining the presence of a given mineral in the ore and in testing the purity of mineral separations where a fluorescent or phosphorescent mineral is involved.

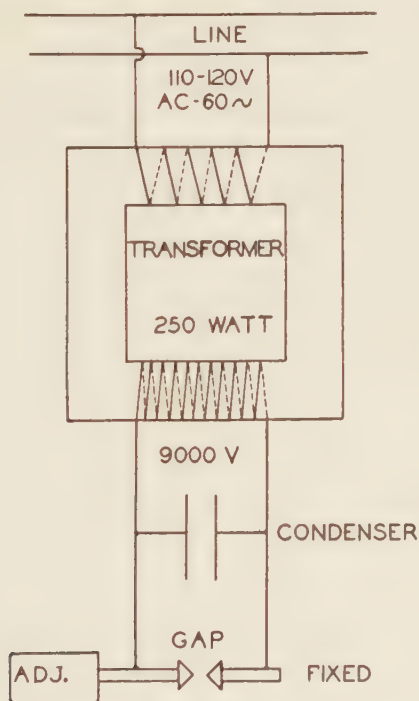


Fig. 1. Electrical layout of spark-gap apparatus.

In a recent article by L. J. Spencer² attention is drawn to this property and the use of the mercury-vapor lamp as a source of ultra-violet rays is described. The writer experimented briefly with the small "Labarc" used in this laboratory as a source of monochromatic light. Whether because it is a less powerful lamp

² Fluorescence of willemite and some other zinc minerals in ultra-violet rays. *Mineralog. Mag.*, 21, 394, 1927.

than the one used by Dr. Spencer or because of inappropriate housing, the effects obtained were far less brilliant than with the iron-arc. It was particularly noted that fluorescence was less vivid but on the other hand several specimens showed phosphorescence after exposure to the mercury arc in which it had not been visible with the spark-gap. It is of course quite to be expected that the range and intensities of ultra-violet waves in the two light sources would be so different as to produce varying effects.

WILLEMITE. Generally fluorescent and sometimes strongly phosphorescent with a green color. The normal Franklin willemite shows both characters. The purest white willemite, however, gives a weak or no reaction. Troostite, the variety of willemite high in manganese, also gives a weak or negative reaction. The veins of radiated fibrous willemite which contain but a little manganese have a phosphorescence so strong that the vivid green glow lasts five minutes or more after brief exposure to the iron-arc. The so-called "black" willemite which is a very pure willemite crowded with minute inclusions of franklinite does not fluoresce.

If no spark-gap is available the phosphorescence of willemite can be very well exhibited by burning a short length of magnesium ribbon close to the specimens. In a dark room the phosphorescent glow is strong.

CALCITE. Pure calcite is negative. Most of the calcite and dolomite of the Franklin ore is mangiferous and then fluoresces in various tones of vivid red to pale pink. In some cases what is apparently calcite has a faint violet fluorescence but the nature of the impurity here is unknown.

CALCIUM-LARSENITE. This new calcium lead silicate has a very vivid fluorescence of lemon yellow color. It is more intense than the fluorescence of willemite. Unlike the latter it does not phosphoresce.

LARSENITE is negative or pale violet.

PECTOLITE. Gives a fluorescence of pure yellow tone probably due to its slight manganese content.

CLINOHEDRITE. Fluoresces with a slightly orange yellow tone not so vivid as pectolite or calcite. It is not easy to distinguish from pectolite by the fluorescence.

MARGAROSANITE. Fluoresces with a rather lively pale violet color.

HARDYSTONITE. Fluoresces with a dull faint violet tint, sometimes negative.

ROEBLINGITE. Is negative or gives a very pale pink fluorescence.

HEDYPHANE. A bluish gray fluorescence, not very distinct.

None of the many other minerals at Franklin of a composition more or less related to the above show fluorescence. The test is, therefore, an effective one for selecting the comparatively small number of species which react. The description of these fluorescent colors in ordinary color terminology is apt to be misleading. No one who has not seen it can realize the peculiar quality of the color in a strongly fluorescent mineral. Its whole mass seems to glow more like a molten metal than a solid.

The appearance of a specimen of calcium-larsenite for example is astonishing. Seen in daylight it is colored throughout white or grayish except for the interspersed grains of black franklinite. But under the spark-gap it is a medley of color. The pale yellow fluorescence of the calcium-larsenite and the green of willemite dominate the color scheme. In cavities, clinohedrite shows areas of orange yellow and larsenite, a very pale violet tint. Hardy-stonite, too, is violet toned while scattered grains of calcite glow with a vivid red.

LARSENITE, CALCIUM-LARSENITE AND THE
ASSOCIATED MINERALS AT FRANKLIN,
NEW JERSEY

C. PALACHE, L. H. BAUER, AND H. BERMAN

A preliminary description of larsenite and calcium-larsenite, new lead silicates, has recently been published.¹ There is little to add to this description of the new minerals except details of the crystal form of larsenite. But the paragenesis is complex and unusual and seems worthy of somewhat full description. The first specimens were found on the picking table but the place of their occurrence in the mine was afterwards located in the North end, 20 feet above the 400' level in the 1080 top-slice. A second locality of calcium-larsenite has been found, also in the North end but on the 1100' level in 80 pillar.

The specimens in hand are in part veins cutting ore, in part replacements of massive, rather coarse willemite-franklinite ore. The calcium-larsenite is all of the latter type and appears to have replaced willemite or in places hardystonite with which it is intimately associated. In the locality on the 1100' level, calcium-larsenite is similarly related to a mixture of glaucochroite and hardystonite with franklinite. The veins are sharply bounded against the granular ore and vary in their contents from place to place. The earliest mineral to form is a massive pink garnet, identical in appearance and refractive index (1.885) with a garnet from another specimen, shown by partial analysis to be andradite. Following this is a coating of hodgkinsonite of the same pink color as the garnet where it is massive. Most surfaces of the open veins show crystals of hodgkinsonite of a pale pink to almost colorless variety, the crystals rather indistinct and with rounded faces. In several specimens devoid of lead silicates the only minerals later than hodgkinsonite are calcite in slender needles or clear prismatic crystals; botryoidal coatings of smithsonite; granular orange colored zincite; and a last coating of snow white needles of willemite forming delicate rosettes. In other parts of the open veins hodgkinsonite was followed by an abundant layer of crystalline clinohedrite with which the slender needles and plates of

¹ *Am. Mineral.*, 13, 142, 1928.

larsenite are contemporaneous. A description of the form and properties of this clinohedrite will be found on page 303. A few spots of dull white massive roebblingite were found in one of the specimens covering clinohedrite crystals. Larsenite is far less abundant than calcium-larsenite and in most of the specimens the two are not associated but in two cases crystals of larsenite occur in cavities in the walls of which calcium-larsenite is present.

In one specimen of calcium-larsenite an area of that mineral an inch across is surrounded by a zone of grayish bementite and about this in turn is a border of a dark brown glassy substance determined optically as neotocite. The latter mineral has been described as the alteration product of bementite² and this would appear to be the case here as well.

TABLE I. COMBINATIONS OF FORMS ON LARSENITE
Numbers in squares indicate number of faces present

	<i>b</i>	<i>a</i>	<i>n</i>	<i>m</i>	<i>s</i>	<i>y</i>	<i>d</i>	<i>w</i>	<i>e</i>	<i>q</i>	<i>t</i>	<i>A</i>	<i>l</i>	<i>C</i>	<i>B</i>	
1	1			2	3	2		2				4			4	
2		1	1	2	4			2	2			4			4	
3							1		2			2			2	
4	1	1		1	4							4			4	Fig. 1
5	2				2							2				Fig. 4
6			1	1	4						4	4	2			
7	2	1	2		4							4				
8	1			1	3	1				1	4	3				Fig. 3
9	1			1	4			2				4			4	Fig. 2
10	2			1	4			1	1			4		1	4	

In Table II are the calculated position-angles and the measured angles of each form.

² Pardee, J. T., Larsen, E. S., and Steiger, G. Bementite and Neotocite from Western Washington. *Jour. Wash. Acad. Sci.*, 11, 25, 1921.

TABLE II. ANGLE TABLE OF LARSENITE

	Symbol	Calculated		Measured		Variation		Number of	
		ϕ	ρ	ϕ	ρ	ϕ	ρ	faces	crystals
<i>b</i>	010	0	90°00'	.....	.....	0°06' - 00°40'	.....	10	7
<i>a</i>	100	90°00'	90 00	.....	90°00'	90 02 - 90 17	.....	3	3
<i>n</i>	210	77 45	90 00	.....	90 00	77 38 - 77 51	.....	4	3
<i>m</i>	110	66 32	90 00	.....	90 00	65 24 - 67 53	.....	8	6
<i>s</i>	120	49 03	90 00	66°26'	90 00	48 54 - 50 43	.....	32	9
<i>y</i>	150	24 45	90 00	.....	90 00	24 24 - 25 57	.....	3	2
<i>d</i>	101	90 00	50 49	90 03	50 55	.....	.....	1	4
<i>w</i>	012	0	14 54	0	15 08	.....	14°47' - 15°32'	7	3
<i>e</i>	111	66 32	53 13	.....	.....	66 41 - 66 46	.....	5	3
<i>q</i>	122	49 03	39 05	47 51	39 37	.....	.....	1	2
<i>t</i>	132	37 32	45 12	37 30	45 13	37 15 - 37 44	45 05 - 45 20	8	10
<i>A</i>	142	29 57	50 52	29 55	50 52	29 51 - 30 00	50 46 - 50 54	35	1
<i>l</i>	131	37 32	63 36	37 06	63 38	36 45 - 37 28	63 34 - 63 45	2	6
<i>C</i>	252	42 40	61 05	42 30	61 10	.....	.....	1	
<i>B</i>	9.8.18	68 54	33 19	.....	.....	69 06 - 69 28	33 11 - 33 15	20	

LARSENITE. CRYSTALLOGRAPHY. The crystals of larsenite are slender needles ten to twenty times as long as they are in cross section, forming an interlacing network in vein cavities. Many of them reach from wall to wall and show no termination but a few stand with one end free and could be detached for measurement. In two specimens only it has the form of thin lustrous plates. Ten crystals were studied in detail and the distribution of forms upon them is shown in TABLE I. The axes were calculated from forty faces of the five forms (120), (142), (132), (111) and (131) with the following result:

$$a:b:c=0.4339:1:0.5324$$

$$p_0=1.2268 \qquad q_0=0.5324$$

The prism zone is generally rounded by striation, one crystal only showing a pronounced flattening parallel to the pinacoid (010). The prism (120) to which the cleavage is parallel is always present and gives good reflections while (110), (210) and (150) are line faces only. The termination is generally dominated by the pyramid (142) the faces of which are excellent and give consistent readings. The calculation of the axes is chiefly based on this form and the prism (120). This pyramid was at first selected as the unit form but it was found that the relation to the chrysolite group of minerals was much better satisfied by the position here adopted. The obtuse edge of this pyramid is generally truncated by a pair of narrow faces of the pyramid (9.8.18) which is close to the position of the much simpler form (112) but deviates consistently from it.

	ϕ	ρ
(9.8.18)	68°54'	33°19'
(112)	66°32'	33°46'

Plate XI shows crystals of larsenite.

Figure 1 shows the prevailing habit. In figure 2 the brachydome is added. Figure 3 shows a habit observed on but a single crystal. The platy habit is illustrated in figure 4. Forms not shown in the figures are very subordinate in development, generally occurring as line faces only. The needles are very slender so that the terminal faces are in all cases exceedingly minute. Because, however, of the high lustre of the mineral they give good measurements despite their minute area.

EXPLANATION OF PLATE XI

Fig. 1. Larsenite. Drawing of a crystal showing the normal termination, with the forms $b(010)$, $m(110)$, $s(120)$, $A(142)$ and $B(9.8.18)$.

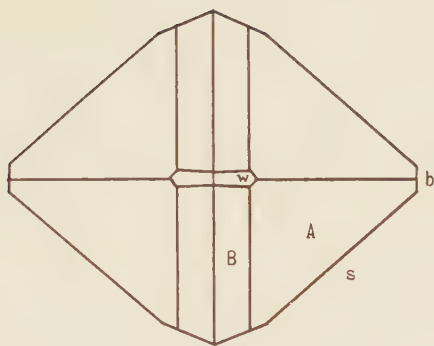
Fig. 2. Larsenite. Drawing in plan of a crystal showing the forms of figure 1 and in addition $w(012)$.

Fig. 3. Larsenite. Plan of a crystal showing the forms $m(110)$, $s(120)$, $q(122)$, $t(132)$, and $A(142)$.

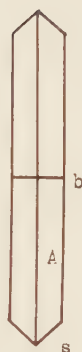
Fig. 4. Larsenite. Plan of a crystal of tabular habit showing the forms $b(010)$, $s(120)$ and $A(142)$.



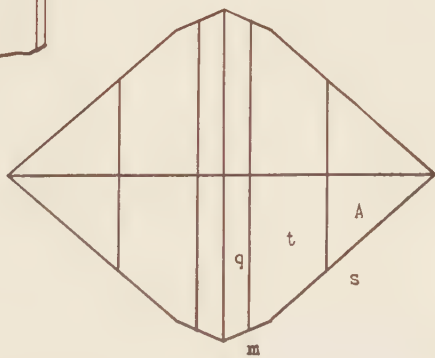
1



2



4



3

PHYSICAL PROPERTIES. The specific gravity of larsenite, determined with the pycnometer on a very small (.075 gr.) pure sample is 5.88. The analyzed sample gave, by the same method, a value of 5.67. This sample was found to contain 9.26 per cent. of clinochroite with a specific gravity of 3.33 and by calculation this gave a value for larsenite of 5.91. The average of the two determinations, 5.90, was taken as the true value but it is evident that the determination requires confirmation on a larger pure sample. Larsenite is about 3 in hardness, has the adamantine lustre characteristic of lead compounds and the platy variety has a somewhat pearly lustre on the surface of the plates. The indices of refraction had to be determined in melted media and may be slightly incorrect because of the heating involved which caused a slight yellowing of the white mineral. With the above exceptions, nothing has been added to the physical data presented in the preliminary paper³ for either larsenite or calcium-larsenite. The same holds true of the chemical data there presented. The analyst, Mr. Bauer, gives the following information as to the method of analysis and chemical properties of the minerals.

"Both minerals dissolve readily in dilute nitric acid giving gelatinous silica. In the oxidizing flame of the blow-pipe larsenite fuses easily to a white enamel, while the unfused portion turns yellow, when further heated in the reducing flame the mass turns black indicating the reduction of the oxide to metallic lead. The calcium-larsenite while not fusing quite so readily shows the same tests in the blow-pipe flames.

About .6 grams of a purified sample of larsenite was obtained for complete analysis. After taking .1056 grams for a Penfield water determination the balance was weighed into two portions for complete analysis. First the silica was obtained from a double evaporation in nitric acid solution, the filtrate from the silica was evaporated to dryness to expel all traces of nitric acid, and the residue dissolved in an accurately adjusted 1% HCl solution. This acidity is essential in order to best precipitate all traces of lead with H_2S . The PbS was filtered off, redissolved and in turn converted to lead sulfate and lead chromate. The filtrates from the lead sulfide and lead sulfate were combined and taken to dryness. The RO group was then removed by precipitation with bromine and ammonia and weighed as R_2O_3 . The weight obtained from (a) was redissolved and the FeO determined by the standard sulphocyanate method. In (b) the MnO was determined by oxidation with ammonium persulfate and subsequent titration with a standard sodium arsenite solution. The lime and magnesia were found respectively by the well known oxalate and pyrophosphate methods. In the filtrate from the magnesia determination the zinc was found by the acid ferrocyanide method. The same procedure was followed with the calcium-larsenite analysis. Due to its fluorescence under the iron-arc a pure sample for analysis was readily obtained by hand picking."

³ See ante p. 334.

The analytical results are as follows:

LARSENITE			
	(a) .2083 gms	(b) .2388 gms	Mean
SiO ₂	16.85	16.88	16.87
PbO	56.66 ¹	56.66	56.66
ZnO	22.70	22.78	22.74
FeO	{ 0.23	{ 0.26	0.10
MnO			0.14
CaO	2.40	2.43	2.42
MgO	0.20	0.20	.20
H ₂ O+110°C	0.76 ²	0.76	.76
	<hr/> 99.80	<hr/> 99.97	<hr/> 99.89

¹ Substituted result from (b).

² Wt. of Sample .1056 grams.

CALCIUM-LARSENITE				
	(a) .4504 gms.	(b) .40 gms.	(c) .3024 gms.	Mean
SiO ₂	24.10		23.98 ³	24.10
FeO	{ 1.05	{ 1.04		0.48
MnO				0.57
CaO	16.30	16.42		16.36
ZnO	30.65	30.49	30.69	30.61
PbO	27.61	27.65	27.38 ³	27.63
MgO	0.22	0.24		0.23
H ₂ O+110°C	0.12 ⁴			0.12
				<hr/> 100.10

³ Discarded in mean.

⁴ Wt. of Sample .2523 gms.

The group relationship of these minerals is as follows:

	a:b:c	Sp. gr.	Cleavage
Larsenite Pb Zn SiO ₄	0.4339 :1: 0.5324	5.9	(120) good
Ca-larsenite (Pb, Ca) Zn SiO ₄	..... ..	4.42	Indistinct
Tephroite (Mn, Mg, Zn) ₂ SiO ₄	0.460 :1: 0.5939	4.12	Pinacoidal
Glaucochroite Ca Mn SiO ₄	0.4409 :1: 0.5808	3.40	(001) poor
Chrysolite (Mg, Fe) ₂ SiO ₄	0.4656 :1: 0.5865	3.37	(010) poor

It is interesting to note in view of the discovery of these lead silicates that in both analyses of glaucochroite (ante p. 308) some lead is reported, showing possibly the presence of the larsenite molecule.

FRIEDELITE, SCHALLERITE, AND RELATED MINERALS

L. H. BAUER AND HARRY BERMAN

The problem of the isomorphism of friedelite and a number of other minerals similar in crystallographic and optical properties, and related chemically, has attracted several investigators. New chemical and physical data recently determined on some minerals of this group by the authors and others, have led to a review of the problem.

The main object of this paper is to point out the isomorphism of friedelite and schallerite, two minerals that occur at Franklin, New Jersey. Friedelite has also been found at other localities. In the course of this study it was found desirable to examine some other probable members of the group and the results of such work are also presented.

GENERAL CHARACTERISTICS OF THE FRIEDELITE GROUP

The following species are accepted by the authors as members of the friedelite group: friedelite, pyrosmalite, schallerite, and molybdophyllite. These minerals have physical properties common to the group, the most marked of which is the perfect basal cleavage. The optical orientation of all the members of the group is identical, i.e., $\alpha = \epsilon = c$. Friedelite and some others of the group exhibit an anomalous biaxial character sometimes, although they are normally uniaxial and negative. The axial angle, however, never exceeds a few degrees. The members of the group are rhombohedral hemimorphic, as determined by crystallographic and X-ray⁶ methods. No crystallographic data are available for schallerite, which has been found only in the massive form.

The general formula for the group may be expressed as: $R_8[(\text{SiO}_3)_x(\text{OH}, \text{Cl})_y(\text{As}_2\text{O}_5)_z] + n\text{H}_2\text{O}$, where $R = \text{Mn}$ and Fe . (In molybdophyllite $R = \text{Mg}:\text{Pb} = 1:1$.) $x = 6$ (in Molybdophyllite $x = 4$), y and z are variable to make up the valency requirements. $n = 3$. The H_2O is variable to a certain extent, probably due to water of crystallization.

TABLE I contains analyses of friedelite and schallerite, made by the senior author and others. TABLE II is a list of the physical properties of the analyzed material of the preceding table, and other values taken from various sources, as noted.

TABLE I.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO ₂	34.45	35.36	34.69	33.99	36.35	34.73	31.44	31.82	32.42	32.76
MnO	51.48	55.80	48.00	50.73	46.67	54.80	44.70	50.20	49.21	51.68
MgO	1.54		0.98	1.45	0.05		2.19		0.71	
FeO	0.68		1.45	0.54	5.27		2.12		0.62	
CaO			0.63		trace		0.36			
ZnO	1.43		1.05	0.77	0.32		0.54		trace	
Cl	0.29		3.43	2.32	3.08	3.42	0.08		0.60	
As ₂ O ₃				1.15			12.24	12.25	7.50	9.01
Al ₂ O ₃	present				0.03				1.59	
H ₂ O	9.74	8.84	+9.08 -1.94	9.40	8.86	7.82	6.55	5.73	7.24	6.55
O = Cl	99.61	100.00	101.25	100.35	100.63	100.77	100.22	100.00	99.89	100.00
	0.06		0.77	0.52	0.69	0.77	0.02		0.13	
Total	99.55		100.48	99.83	99.94	100.00	100.20		99.86	

1. Low-chlorine friedelite—Franklin, L. H. Bauer, analyst. Cat. No. 34826.

2. Chlorine-free friedelite—calculated composition.

3. Friedelite—Buckwheat Mine, Franklin, W. T. Schaller, analyst. Cat. No. 87123.

4. Friedelite—Franklin, L. H. Bauer analyst.

5. Friedelite—Taylor Mine, Franklin, R. B. Gage, analyst.

6. Friedelite—calculated composition.

7. Schallerite (type material) Franklin, Reanalysis, L. H. Bauer, analyst.

8. Schallerite—calculated composition (type I).

9. Schallerite—Franklin, L. H. Bauer, analyst (type II).

10. Schallerite—calculated composition (type II).

TABLE IIa. PHYSICAL PROPERTIES OF THE MEMBERS OF THE FRIEDELITE GROUP AND RELATED MINERALS

	1. Friedelite anal. 3 table I	2. Friedelite anal. 4 table I	3. Schallerite anal. 9 table I	4. Schallerite anal. 7 table I	5. Pyrosmalite	6. Molybdophyllite
Crystal system	rhombohedral	rhombohedral	rhombohedral?	rhombohedral?	rhombohedral	rhombohedral
Cleavage	(0001)	(0001)	(0001)	(0001)	(0001)	(0001)
Optical Character	(-)	(-)	(-)	(-)	(-)	(-)
Optical Orientation	$\epsilon = c$	$\epsilon = c$	$\epsilon = c$	$\epsilon = c$	$\epsilon = c$	$\epsilon = c$
2V = axial angle	0°	0°	0°	0°	0°	0°
ω	1.654	1.656	1.681	1.704	1.675	1.815
ϵ	1.625	1.62	1.643	1.679	1.636	1.761
Birefringence ($\omega - \epsilon$)	.029	.03	.038	.025	.039	.054
Specific Gravity	3.041	3.059	3.339	3.339	3.153	4.72

Column 4—reference 6.

Column 5—E. S. Larsen—*Bull.* 679 U. S. G. S.

Column 6—reference 8.

TABLE IIb.

	7. Bementite	8. Hematolite	9. Dixenite type I	10. Dixenite type II	11. Mcgovernite	12. Parsetten- site	13. Errite
Crystal system	Orthorhombic	rhomboidal	rhomboidal?	rhomboidal?	rhomboidal	hexagonal?	hexagonal?
Cleavage	(001)	(0001)	(0001)	(0001)	(0000)	(0001)	(0001)
Optical character	(-)	(-)	(-)	(-)	+	(-)	(-)
Optical orientation	$\alpha = c$	$\epsilon = c$	$\alpha = c$	$\alpha = c$	$\epsilon = c$	$\epsilon = c$	$\epsilon = c$
2V = axial angle	small	0°	small	small	0°	small	small
ω	1.650	1.735	1.96	1.757	1.754	1.576	1.575
ϵ	1.624	1.716		1.735		1.546	1.547
Birefringence ($\omega - \epsilon$)	.026	.019			very weak	.030	.028
Specific gravity	2.98 3.20	3.416	4.2	3.485	3.719	2.590	2.681

Column 7—reference 9.

Column 9—reference 12.

Columns 12-13—reference 14.

FRIEDELITE

The formula of friedelite as given by Groth,¹ Dana,² and Palache³ is in the orthosilicate form. Zambonini,⁴ however, in a later paper, prefers the metasilicate form, and Aminoff⁵ in a recent paper also considers friedelite as a metasilicate. In a discussion of the probable relation of friedelite and schallerite, in the original description of the latter mineral, Gage, Larsen and Vassar⁶ consider them as probably metasilicates. In this paper friedelite and the other members of the group are considered as metasilicates mainly because it seems to simplify the discussion. The formula here adopted for friedelite is: $\text{Mn}_8[(\text{SiO}_3)_6(\text{OH}, \text{Cl})_4] + 3\text{H}_2\text{O}$, derived from the same composition, Column 6, TABLE I, as the orthosilicate formula of Palache.³ Friedelite seems to vary in its chlorine content, as is shown by the analyses in TABLE I. The analysis in column 1 is that of an almost chlorine free friedelite.

Column 2 gives the calculated composition for the chlorine free variety. In column 4 the friedelite analysis carries a small amount by arsenic trioxide indicating that it is probably a "connecting link" with the related arsenic-bearing schallerite.

Friedelite is rhombohedral hemimorphic, with a perfect basal cleavage showing a pearly luster on the cleavage plane. It is uniaxial negative with a medium birefringence. The mineral exhibits anomalous biaxial character quite frequently, the axial angle, however, does not exceed a few degrees.

SCHALLERITE

In columns 7, 8, 9, 10 are given analyses for schallerite and calculated compositions for the formulae suggested. The re-analysis of the type material (column 7) indicates that the arsenic is present as the trioxide rather than the pentoxide as reported in the original description.⁶ The method used by the senior author in determining the state of oxidation of the arsenic in the schallerite is identical with that given by him in the description of mcgovernite. The formula here suggested for schallerite is: $\text{Mn}_8[(\text{SiO}_3)_6 \cdot (\text{OH})_{1.2}(\text{As}_2\text{O}_6)_{.7}] + 3\text{H}_2\text{O}$, for which the calculated composition is given in column 8. This formula differs from that of friedelite in that part of the hydroxyl and chlorine is replaced by the pyroarsenious acid radical, the total valency values remaining the same.

The optical properties and general physical characteristics of schallerite and friedelite are similar, so much so, in fact, that there is no way of distinguishing them except by physical measurements or chemical examination. Schallerite is readily recognized by its higher index of refraction and higher specific gravity, as shown in TABLE II, in which the physical properties of the group are given.

The second occurrence of schallerite, analysis 9 of TABLE I, is somewhat less rich in As_2O_3 . The formula assigned, in accordance with the schallerite and friedelite formulae above given, is: $\text{Mn}_8[(\text{SiO}_3)_6 \cdot (\text{OH})_2(\text{As}_2\text{O}_6)^{1/2}] + 3\text{H}_2\text{O}$, in which less of the hydroxyl is replaced by the pyroarsenious acid radical. The index of refraction and the specific gravity of this material are somewhat lower than that of the original schallerite, as is to be expected from its lower arsenic content.

PYROSMAILITE

The isomorphism of pyrosmalite with friedelite has been well established by others. The formula, written in the manner of friedelite is: $R_8[(\text{SiO}_3)_6(\text{OH}, \text{Cl})_4] + 3\text{H}_2\text{O}$, where $R = \text{Fe}^{++}$, Mn^{++} . The introduction of iron in the structure of pyrosmalite raises the index of refraction somewhat, as is seen in the values for the physical constants in TABLE II.

MOLYBDOPHYLLITE

Aminoff⁵ has placed this mineral in the friedelite group as a result of an X-rays study despite the fact that it seems to differ markedly in its chemical constitution. The formula here suggested to show its relation to the other members of the group is: $R_8[(\text{SiO}_3)_4(\text{OH})_8] + \text{H}_2\text{O}$, where $R = \text{Mg}:\text{Pb} = 1:1$. This formula departs from the others given above in that magnesium and lead replace the manganese, and there is less of the metasilicate present in proportion to the hydroxyl. The general structure of the formula, however, remains the same. The composition calculated from the formula together with the analysis by Flink⁸ is given below.

	1.	2.
SiO_2	18.15	17.35
MgO	11.71	11.68
PbO	61.09	64.47
Na_2O	0.82	
K_2O	0.69	
Al_2O_3	0.46	
H_2O	6.32	6.50
	<hr/> 99.24	<hr/> 100.00

1. Molybdomphylite—Långbän, G. Flink analys.

2. Calculated composition for formula in text.

MINERALS SHOWING LESS CERTAIN RELATION TO THE FRIEDELITE GROUP

BEMENTITE

Bementite has been shown by Pardee, Larsen, and Steiger⁹ to be the same as karyopillite. The probable relationship of karyopillite to friedelite has been pointed out by Groth¹⁰ and Clarke.¹¹ Adopting the average of three analyses, by Steiger

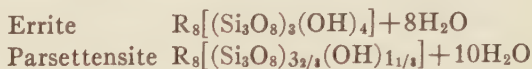
and König, the following formula may be written for bementite: $\text{Mn}_8[(\text{SiO}_3)_7(\text{OH})_2] + 4\text{H}_2\text{O}$. Bementite is said to be orthorhombic with three pinacoidal cleavages. The optical properties, however, are such that it may without difficulty be considered as similar to the members of the friedelite group. In bementite $\alpha = c$ as in friedelite. It is sensibly uniaxial and is negative. The likeness of the physical properties of these two minerals comes out clearly in TABLE II. Genetically it is more difficult to trace relationship between them and further study is needed before any definite conclusion can be reached.

Dixenite¹² and mcgovernite⁷ are somewhat similar in composition and may well be related to the friedelite group. Flink assigns to dixenite the formula $\text{R SiO}_3 \cdot 2\text{R}_2(\text{OH})(\text{AsO}_3)$. Mcgovernite may be written $\text{R}_2\text{SiO}_4 \cdot \text{R}_2[(\text{OH})(\text{AsO}_3 \cdot \text{AsO}_4)] \cdot 3\text{R}(\text{OH})_2$. Optically the two minerals differ somewhat for dixenite is optically negative, mcgovernite positive and with a lower birefringence. What has just been said refers to dixenite, type I. Dixenite, type II, also from Långban, which has not yet been analyzed approaches mcgovernite more nearly in optical properties and they have the same appearance, with highly micaceous structure, pearly luster and a bronze-red color. It seems not unlikely that this form of dixenite will prove to have a composition very similar to that of mcgovernite.

Hematolite,¹³ a poorly defined species from Nordmark, Sweden, is so much like members of the friedelite group in its physical properties that a close chemical relationship probably exists. The analyses as yet are obviously unsatisfactory but they indicate that hematolite differs from schallerite chiefly in the absence of silica which is replaced by the hydroxyl and the arsenate radical. The arsenic was found to be present in two states of oxidation by the senior author. Sufficient material for a quantitative analysis was not available.

Parsettensite and errite,¹⁴ two recently described minerals from Switzerland have been suggested as members of this group. The authors believe that there is not a sufficiently close relationship chemically, although they have the same pearly cleavage on the base and are essentially hydrous silicates. There is a considerable excess of silica in any formula analogous to that of friedelite which can be assigned to them. It is, however, possible to consider them related if one assumes that the trisilicate radical may replace the

metasilicate. The formulae may be written to conform with that of friedelite in the following manner:



CONCLUSION

This study suggests the necessity of further work on some of the minerals discussed. The work of Aminoff⁶ on X-ray crystal data of friedelite, pyrosmalite and molybdophyllite should be extended to include bementite, schallerite, dixenite, mcgovernite, and hematolite. A clue to the complex structural relations between minerals in which different acid radicals replace each other may be gained by such an x-ray study.

Further analyses of hematolite and dixenite of the second type are needed.

The authors wish to express their appreciation of valuable suggestions and criticisms offered by Professor Palache and Professor Larsen of Harvard University.

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NORBERGITE FROM FRANKLIN, NEW JERSEY

ESPER S. LARSEN, L. H. BAUER AND H. BERMAN

The mineral norbergite recently described by Geijer¹ is an abundant mineral in many museums, as most of the minerals labelled chondrodite or humite from Franklin, N. J., are norbergite. All such specimens examined in the Harvard Collections proved to be at least in part norbergite. The norbergite occurs in a coarsely crystalline limestone from the Nicoll Quarry, and grains or crystals are commonly several millimeters across and some are a decimeter across. For the most part crystal faces are entirely lacking, but one crystal suitable for measurement was contained in the Harvard Collection to which it had been presented by Dr. H. Ungemach of Paris in 1906.

In thin sections many of the norbergite grains show irregular, rounded to embayed cores of chondrodite and these cores suggest that the norbergite has replaced the chondrodite, though it may simply have grown about the chondrodite as a nucleus. The chondrodite is more nearly colorless than the norbergite, has little pleochroism, has a higher index of refraction than the norbergite and shows polysynthetic twinning which ends abruptly at the norbergite. In no case was the norbergite observed to be twinned. This fact leads to the conclusion that norbergite is orthorhombic.

The norbergite varies in color from tawny (Ridgway's 13" j) to chamois (Ridgway's 19" b) and the lighter colored varieties have lower indices of refraction than the darker, indicating lower iron content. It has a hardness of about $5\frac{1}{2}$ and in general appearance resembles the other members of the humite group.

The optical properties of norbergite from Franklin are similar to those reported by Geijer for the mineral from Norberg. It is optically +, 2V about 50° , dispersion slight. The indices of refraction vary somewhat; those of the darker, analyzed material are given in column 1, TABLE I, those for the chamois-colored crystals in column 2, and those found by Geijer for the Norberg mineral in column 3. The measurements of the mineral were made by the immersion method using monochromatic light and should be in error not more than ± 0.001 .

¹ Geijer, Per. Some Mineral Associations from the Norberg District, *Sveriges. Geol. Unders. Arsbok*, 20, No. 4, 1926.

The norbergite is distinctly pleochroic in thin sections and in this respect resembles the other members of the humite group. For the analyzed materials α is pale yellow, β is very faint yellow, and γ is sensibly colorless. The lighter colored varieties are more faintly colored.

A sample of the Franklin norbergite containing about 2 per cent. of admixed chondrodite, was analyzed by Bauer and the results are shown in column 1, TABLE I. In column 3 the analysis of the norberg mineral by Bygden is shown, and in column 4 the composition of the theoretical molecule, $\text{MgF}_2 \cdot \text{Mg}_2\text{SiO}_4$. The two analyses are much alike and are near the theoretical composition. The Franklin mineral is high in alumina and low in water and iron.

TABLE I. ANALYSIS AND PROPERTIES OF NORBERGITE.

	1.	2.	3.	4.
	Franklin tawny	Franklin chamois	Norberg	$\text{MgF}_2 \cdot \text{Mg}_2\text{SiO}_4$
SiO_2	28.63		28.54	29.6
Al_2O_3	3.12		0.09	
Fe_2O_3			0.69	
FeO	0.73		0.82	
MgO	59.42		56.45	59.6
CaO			1.01	
MnO	0.04		0.18	
F	12.78		13.70	18.7
H_2O	0.32		2.90	
CO_2			1.21	
	<hr/>		<hr/>	<hr/>
	105.04		105.59	107.9
Less O for F	5.38		5.77	7.9
	<hr/>		<hr/>	<hr/>
	99.66		99.82	100.0
α	1.565	1.561	1.563	
β	1.570	1.566	1.567	
γ	1.591	1.587	1.590	
2V	49°	50°	49°30'	
Sp. Gr.	3.20			
H	5 $\frac{1}{2}$			

CRYSTALLOGRAPHY. Penfield and Howe² on the assumption that there is a regular progression in the value of the c crystallographic

² Penfield, S. L. and Howe, W. T. H. On the Chemical Composition of Chondrodite, Humite and Clinohumite. *Am. Jour. Sci.*, 48, 188, 1894.

axis with a change in the chemical composition of the members of the humite group, predicted the axis for norbergite and later Sjögren³ gave the name prolectite to a member of the humite group from Nordmarken as a result of a crystallographic study that seemed to show an agreement between his mineral and the mineral predicted by Penfield and Howe. Recently Geijer⁴ has shown that the original prolectite is identical with chondrodite.

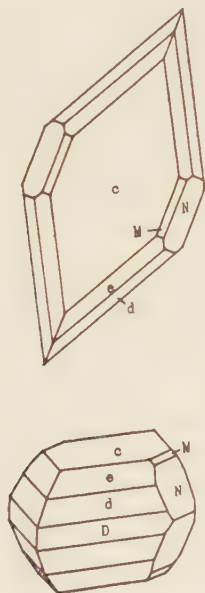


FIGURE 1. NORBERGITE. Drawing of a crystal showing the forms c (001), M (011), N (021), D (110), e (111) and d (221).

An X-ray study of the members of the humite group by Bragg and West⁵ showed that the members of the humite group with 1, 3, or 5 Mg_2SiO_4 to 1 of $\text{Mg}(\text{F},\text{OH})_2$ should be orthorhombic while prolectite with 1 molecule of Mg_2SiO_4 had been described as monoclinic. Our study confirms the conclusions of Bragg and West as both the optical data and the crystallographic study show

³ Sjögren, Hj. Contrib. to Swedish Mineralogy, *Bull. Geol. Inst. Upsala*, Vol. I, 40, 1893.

⁴ *Loc. cit.*

⁵ Bragg, W. L. and West, J. The Structure of Certain Silicates, *Proc. Royal Soc. London*, CXIV, 614, 1927.

that norbergite is orthorhombic. The orthorhombic development is shown by the one good crystal reproduced in figure 1.

Although the crystal here studied is not suited for accurate determination of the crystallographic constants, the values actually determined are given, to be compared with those predicted by Penfield and Howe and used by Dana and others. The orientation of Goldschmidt⁶ is, however, preferred because his treatment of the humite group is in accordance with the results from X-ray studies obtained independently by Bragg and West.

TABLE II gives the measured and calculated angles for the Franklin norbergite, as well as the calculated angles from the theoretical axes proposed by Penfield and Howe. The last column of the table is the preferred position, similar to the position given to humite by Goldschmidt. The letters assigned to the forms are those for the corresponding forms of humite as given in the Winkeltabellen.

TABLE II. ANGLE TABLE OF NORBERGITE.

	Dana Position					
	Observed Mean		Calculated		Theoretical Axes	
	ϕ	ρ	ϕ	ρ	ϕ	ρ
			$p_0:q_0 = 1.723:1.897$		$p_0:q_0 = 1.746:1.886$	
			$a:c = 1.10:1.897$		$a:c = 1.080:1.886$	
<i>c</i> (100)	90°00'	90°00'	90°00'	90°00'	90°00'	90°00'
<i>M</i> (110)	42 25	90 00	42 15	90 00	42 47	90 00
<i>N</i> (120)	24 26	90 00	24 26	90 00	24 50	90 00
<i>D</i> (011)	0	62 12	0	62 12	0	62 04
<i>e</i> (111)	42 25	68 14	42 15	68 41	42 47	68 45
<i>d</i> (122)	24 26	64 24	24 26	64 21	24 50	64 45

Goldschmidt Position
(Values of Col. 2 above with changed axes)

	Calculated	
	ϕ	ρ
	$p_0:q_0 = .5804:1.10$	
	$a:c = 1.897:1.10$	
<i>c</i> (001)	.....	0°00'
<i>M</i> (011)	0°00'	47 13
<i>N</i> (021)	0 00	65 34
<i>D</i> (110)	27 48	90 00
<i>e</i> (111)	27 48	51 13
<i>d</i> (221)	27 48	68 07

⁶ Goldschmidt, V. KRYSTALLOGRAPHISCHE WINKELTABELLEN, 181, 1897.

TABLE III gives the axial ratios compared for the three positions adopted by Dana, Goldschmidt, and Bragg and West. For norbergite the a and c axes are interchanged in the Dana and Goldschmidt positions. In the Bragg position the a axis is chosen as unity. The lengths in Ångstrom units are given for the members of the group, as determined by Bragg and West. The approximate interplanar spacings along the axes for norbergite should be, according to the axial ratio from the calculated values, $4.65\text{Å} : 10.23\text{Å} : 8.82\text{Å}$. If the theoretical values for "prolectite" are used the interplanar spacing is: $4.74\text{Å} : 10.23\text{Å} : 8.932\text{Å}$ which is probably more accurate than the spacings derived from the measured values. In order to carry out the theory of a progression in the value of the c axis, the c value should probably be halved, so that $c = 4.466\text{Å}$.

TABLE III. COMPARISON OF AXIAL RATIOS IN VARIOUS POSITIONS.

	Dana Position			Goldschmidt Position	
	Syst.	$a:b:c$	β	$a:b:c$	β
Norbergite	Or.	1.10 :1:1.897		1.897 :1:1.10	
Chondrodite	Mcl.	1.0863:1:3.1447	90°00'	1.6624:1:1.0832	109°01'
Humite	Or.	1:1.0802:4.4033		2.207 :1:1.0803	
Clinohumite	Mcl.	1.0803:1:5.6588	90°00'	1.4387:1:1.0793	100°48'

Bragg and West Position						
	Axial Ratios		Absolute lengths of Axes			
	$a : b : c$	β	a	b$	|| (001)$	
Norbergite	not yet studied					
Chondrodite	1:2.170:1.663	109°02'	4.733 Å	10.27 Å	7.44 Å	
Humite	1:2.159:2.201		4.738	10.23	10.43	
Clinohumite	1:2.160:2.878	100°50'	4.75	10.26	13.43	

THE OPTICAL PROPERTIES OF THE HUMITE GROUP

ESPER S. LARSEN

A considerable number of specimens of the humite group were examined optically in an attempt to find some consistent differences that would enable one to quickly and with assurance, distinguish between the members of the group. Assuming that the specimens were correctly labelled, the resulting data and in particular the indices of refraction for each member of the group showed a surprisingly wide variation and within about the same range for each of the species, so that no satisfactory data for determinative purposes was had and the suspicion was raised that many of the specimens might be incorrectly labelled. It was accordingly decided that any reliable data on the group must be based on the examination of material that had been analyzed or otherwise positively identified.

I was fortunate enough to secure the material studied by Penfield and Howe¹ from Professor Ford of Yale University, and that studied by Sjögren² from Professor Aminoff of Stockholm. I express my sincere thanks to Professors Ford and Aminoff for the use of these materials.

The study was made by the immersion method, and the indices of refraction were determined in sodium light and should be in error ± 0.001 . Some of the plates of Sjögren showed zonal growths.

All of the specimens examined, except the one from Franklin, associated with norbergite, are optically +, and all have large to very large axial angles. The pleochroism is stronger for the darker colored specimen and in all the pleochroic formula is: X = yellowish brown; Y = paler yellowish brown; Z = colorless.

TABLE I gives the indices of refraction for five analyzed specimens of chondrodite from as many localities, for a specimen that was similar to the analyzed sample from a sixth locality and for the mineral from four other localities. The indices of refraction for all of the five analyzed specimens are very much alike, those

¹ Penfield, S. L. and Howe, T. H. On the Chemical Composition of Chondrodite, Humite, and Clinohumite. *Am. J. Sc.*, **47**, 188–200, 1894.

² Sjögren, Hj. Chondrodite von Kafveltorp, *Zeit. Kryst. Min.*, **7**, 113–152, 1882.

Beiträge zur Mineralogie Schwedens, *Bull. Geol. Inst. Upsala*, **1**, 1–54, 1892; **2**, 39–54, 1894.

for the Franklin mineral are considerably lower, while those for the Weston, Nordmark, Custer County, and Tilly Foster minerals are much higher. Analyses are available for the mineral from Nordmark and Tilly Foster but the exact materials that furnished the analyses were not available for optical study.

TABLE II. ANALYSES AND OPTICAL PROPERTIES OF HUMITE

	Monte Somma	Vesuvius Yale 4102	Nordmark Sjögren Brownish	Nordmark Sjögren Yellowish
	Light	dark	yellow	gray
SiO ₂	36.63	36.74	35.44	35.21
TiO ₂			0.07	0.07
MgO	56.45	56.31	47.22	48.33
CaO			0.17	0.11
FeO	2.35	2.22	10.96	7.93
MnO			1.47	1.69
Al ₂ O ₃			0.19	0.07
Fe ₂ O ₃			0.68	1.06
F	3.68	3.96	3.79	4.59
K ₂ O			0.17	0.20
Na ₂ O			0.29	0.34
H ₂ O+	2.45	2.13	1.28	} 1.85
H ₂ O—				
	100.96	101.36	101.73	101.45
O for F	1.26	1.66	1.60	1.93
	99.70	99.70	100.13	99.52
Sp. Gr.	3.194	3.183	3.32	3.24
	3.201	3.225		
α	1.621 ³	1.625	1.632 ¹⁰	
β	1.627	1.635	1.643	
γ	1.649	1.656		
2V		70°		

REFERENCES FOR TABLES I AND II

³ Barth, Tom. On Contact Minerals from the Pre-Cambrian in Southern Norway, *Norsk. Geol. Tid.*, **VIII**, 94-96, 1924.

⁴ von Eckermann, Harry. The Rocks and Contact Minerals of the Mansjö Mountain, *Geol. For., Stockholm*, 279-383, 1922.

⁵ Eskola, Pentti. The Contact Phenomena Between Gneiss and Limestone in Western Massachusetts, *Jour. Geol.*, **XXX**, 270, 1922.

⁶ Optical data on brown crystals similar to those analyzed but not on identical material.

⁷ Shannon, E. V. The Minerals of Idaho. *U. S. Nat. Mus., Bull.* **131**, 333-334, 1926.

⁸ Specimens from Tilly Foster gave:

α	1.627	1.632	1.635	1.643
β	1.638	1.640	1.645	1.655
γ	1.657	1.661	1.663	1.670

The last figures are by Gillson, J. L., *Am. Mineral.*, **11**, 284, 1926.

⁹ Optical data not closely tied to the analyses but on specimen 4806 of the Brush Collection which is very pale brown and answers the description of the analyzed specimen.

¹⁰ No. 62 Plate 2 of Sjögren—Optical data not closely tied to analysis.

TABLE III. ANALYSES AND OPTICAL PROPERTIES OF CLINOHUMITE.

	Vesuvius Yale	Vesuvius Brush	Nordmark Sjögren	Chaffey's ¹² Lake, Ontario	Piedmont ¹³
	4143	2046	No. 63		
SiO ₂	37.78	38.03	35.86	37.42	36.83
TiO ₂			.06	1.14	1.92
MgO	53.05	54.00	44.66	56.32	51.53
CaO			trace		
FeO	5.64	4.83	14.25	1.27	4.90
MnO			1.19	0.10	.28
Al ₂ O ₃					0.07
Fe ₂ O ₃			0.22	0.46	0.42
F	3.58	2.06	4.16	5.04	0.03
K ₂ O			0.15		
Na ₂ O			0.29		0.12
H ₂ O+	1.33	1.94	1.58	0.56	{ 3.04
H ₂ O—					{ 0.12
	100.38	100.86	102.42	102.31	99.26 ¹³
O for F	1.50	.86	1.75	2.12	
	99.88	100.00	100.67	100.19	
Sp. Gr.	3.219	3.184	3.35	3.17	
	3.258	3.222			
α	1.632	1.625 ¹⁴	1.652 ¹¹	1.628	1.664 ¹¹
β	1.644	1.638	1.663	1.642	1.673
γ	1.664	1.653			1.698
2V	74°	near 90°	76°27'		62°
Ext.			12°-15°		70°29'

REFERENCES FOR TABLE III.

- ¹¹ Optical data not closely tied to analyses.
¹² Walker, T. L., and Parsons, A. L.—Clinohumite from Chaffey's Lake, Ontario. *Contr. Can. Min.*, p. 17-18, 1927.
¹³ Zambonini, F., —Sur la veritable nature du Titanolivine de la valler d'Ala (Piedmont), *Bull. Soc. Fr. Minr.*, XLII, 1-30, 1919. Contains PbO 0.14, BaO 1.30, Cr₂O₃ 0.03, NiO 0.07, Optical data by Larsen.
¹⁴ Not uniform—Indices vary ± 0.005 or more. Data are for about averages.

In TABLE II optical data are given for three analyzed specimens of humite from two localities.

In TABLE III optical data are given for five analyzed specimens of clinohumite from four localities. The corresponding data for two specimens of analyzed norbergite are given in the preceding paper.

Assembling the data for the four members of the humite group, TABLE IV shows that on the whole, as the Mg₂SiO₄ increases in amount the indices of refraction increase, but there is much overlapping. The norbergite occupies a low range and can be distinguished from the others by its indices of refraction. Most of the analyzed chondrodites have β between 1.616, and 1.622, and are higher than any of the norbergites and lower than any of the humites but some of the chondrodites have β as high as any clinohumite except that from Piedmont. The humites mostly have β lower than does clinohumite but there is overlapping.

TABLE IV. OPTICAL DATA FOR THE HUMITE GROUP.

Compo- sition	Norbergite Mg(OH, F) ₂ · Mg ₂ SiO ₄	Chondrodite Mg(OH, F) ₂ 2Mg ₂ SiO ₄	Humite Mg(OH, F) ₂ 3Mg ₂ SiO ₄	Clinohumite Mg(OH, F) ₂ · 4Mg ₂ SiO ₄
α	1.561-1.563	1.601-1.643	1.621-1.632	1.623-1.664
β	1.566-1.570	1.616-1.655	1.627-1.643	1.636-1.673
γ	1.587-1.590	1.636-1.670	1.649-	1.651-1.698
Ext.	Orth.	22°-29°	Orth.	7°-15°
2V	45°-50°	73°-90°	70°-	62°-90°

The variation in the indices of refraction is brought out by comparing the data for the three minerals (chondrodite, humite, and clinohumite) from the same localities. Such data are available from Vesuvius and from Nordmark and are shown in TABLE V. For both localities the indices of refraction of the chondrodite

are lowest, that for humite intermediate, and that for clinohumite highest though for the Vesuvius mineral the differences are not great.

For each species the Nordmark mineral has considerably higher indices of refraction and iron content than the Vesuvius mineral.

TABLE V. A COMPARISON OF MEMBERS OF THE HUMITE GROUP FROM VESUVIUS AND FROM NORDMARK

From Vesuvius					
	Chondrodite	Humite		Clinohumite	
α	1.609	1.621	1.625	1.632	1.625 \pm
β	1.619	1.627	1.635	1.644	1.638 \pm
γ	1.641	1.649	1.656	1.664	1.653 \pm
FeO+MnO	3.66	2.35	2.22	5.64	4.83
F	5.15	3.68	3.96	3.58	2.06
H ₂ O	2.82	2.45	2.13	1.33	1.94

From Nordmark			
	Chondrodite	Humite	Clinohumite
α	1.619	1.632	1.652
β	1.632	1.643	1.663
γ	1.653		
FeO+MnO	11.78 ?	9.62	15.44
F	5.40 ?	4.59	4.16
H ₂ O	2.30 ?	1.85	1.58

CONCLUSIONS. An attempt to correlate the chemical composition with the optical constants is disappointing. One would expect a simple and systematic relation in which the indices of refraction increase with the iron and titanium content and decrease with the increase in fluorine. There appears to be some tendency in this direction as indicated by the Nordmark minerals which are high in iron and have high indices of refraction but the relations are far from simple. While for the analyzed chondrodites, the optical data are rather uniform ($\beta=1.616$ to 1.622) although there is considerable variation in chemical composition (FeO+MnO=2.64 to 6.62); the Tilly Foster mineral shows very nearly the chemical composition of the Kaveltorp mineral described by Penfield and Howe, yet its indices of refraction are much higher (for Kaveltorp $\beta=1.620$ for Tilly Foster $\beta=1.645$). These data are so inconsistent as to lead one to the suspicion that some constituent, such as titanium, has been overlooked in the Tilly Foster mineral.

CHLOROPHAEITE, SIDEROMELANE AND PALAGONITE FROM THE COLUMBIA RIVER PLATEAU

MARTIN A. PEACOCK*

AND

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SUMMARY

The three mineraloids, chlorophaeite, sideromelane and palagonite are characteristic of Kainozoic basaltic fields. From a new analysis of chlorophaeite from Oregon and existing analyses of materials from Scotland and India the approximate formula: $(\text{Fe,Al})_2\text{O}_3 \cdot 2(\text{Mg,Fe,Ca})\text{O} \cdot 4\text{SiO}_2 + 10\text{H}_2\text{O}$ is derived. It is urged that the definition of chlorophaeite be extended to cover all hydrous, amorphous, pitch-like materials of deuteritic origin, some of which have been named palagonite, in basalts and dolerites.

An argument is advanced supporting the continued use of

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sideromelane, as distinct from tachylyte, as a specific name for ideal basaltic glass formed under conditions of specially rapid cooling.

It is shown that a chemical and genetic distinction exists between chlorophaeite and palagonite; and that palagonite should properly be restricted to its original significance, namely a gel produced essentially in the hydration of sideromelane by water or water vapor of exotic origin.

INTRODUCTION

The terms chlorophaeite, sideromelane and palagonite were all proposed before the petrographic microscope was in common use, and consequently the original descriptions of these materials lack the precision now desirable. Subsequent descriptions are few and the localities to which they refer are widely scattered. As, in addition, none of these three materials possesses the constancy of chemical composition and the habit of crystalline growth proper to mineral species in the strictest sense, it is thus small wonder that their respective definitions in the works of reference are not wholly adequate, and that writers are not entirely in agreement in their acceptance and usage of the terms.

As far as we are aware chlorophaeite and sideromelane have not been previously reported from America; palagonite has occasionally been mentioned in a general sense. The recognition of the three materials typically developed in the eruptives of the Columbia River Plateau is due to one of us (Fuller) who also supplies the notes on the field relations; the other, having had previous experience with these materials, is chiefly responsible for the laboratory study and the discussion.

The main object of this communication is to record new occurrences of chlorophaeite, sideromelane and palagonite; and, from a study of this favorable material in relation to some existing descriptions, to suggest natural definitions for these materials, and thereby, if possible, to stabilize the usage of the three terms.

CHLOROPHAEITE

OCCURRENCE. Chlorophaeite occurs in a Kainozoic dyke, 55 feet in thickness, cutting Columbia River Basalt in the Grande Ronde Valley just south of the town of Anatone in southeast Washington.

HAND-SPECIMEN. A specimen from the center of the dyke is a dark, compact, medium-grained, apparently fresh rock in which

small feldspar tablets are the only recognizable primary minerals. Conspicuous on the broken surface are many circular or ovoid areas representing sections of spheroidal bodies ranging from 1 mm. to 8 mm. in diameter, with an average of about 5 mm., and constituting about 10 per cent. of the bulk of the rock. A few of these amygdales are composed of a very thin lining of an essentially black, pitch-like material and a filling of quartz or of quartz and calcite; the great majority, however, are composed wholly of the black material which also occurs in thin films along joint planes in the rock.

Another specimen from the dyke, taken at about three feet from the margin, has a finer texture than the above specimen. This rock carries about the same proportion of the black material which in this case appears in a swarm of pellicles averaging about 1 mm. in diameter.

When freshly fractured in the field the pitch-like amygdale material is green; on exposure the color rapidly darkens to a deep orange which is nearly black.¹ This color change is characteristic of chlorophaeite and is denoted by the roots from which the name is derived. In small chips the chlorophaeite is opaque with a slight deep-brown translucency at thin edges. The lustre is jet-like to pitch-like; the fracture is conchoidal, and the material may be crumbled with the fingers due to pre-existing networks of fine cracks. The hardness is usually between 2 and 3, but sometimes a fragment will just scratch calcite. The streak of the powder is brown. The specific gravity measured by suspending fragments in suitable mixtures of carbon tetrachloride and bromoform is not quite constant; the majority of fragments, however, remained suspended in a liquid whose specific gravity was found to be 2.267 at 28°. In the reducing flame the material loses its lustre and changes with some decrepitation into a black, readily crumbled, magnetic mass.

MICROSTUDY. In thin section² the coarser phase of the chlorophaeite-bearing rock is seen to be essentially an aggregate of tabular andesine and subhedral brown augite of coarse inter-

¹ The green color is well preserved in the dense, chilled border phase; in the coarse, central portion of the dyke the dark color has already developed.

² We are indebted to Mr. Aaron C. Waters of Yale University, for kindly preparing the thin sections studied in this paper. Mr. Waters also offered helpful comments on the finished manuscript.

granular texture enclosing earlier needles of apatite and irregular grains of titaniferous magnetite as rather abundant accessories. Between the larger components there is a scanty mesostasis of similar constitution.

Chlorophaeite occurs filling the larger circular cavities, and also as a thin impregnation intimately penetrating the body of the rock. In the cavities the chlorophaeite is orange-brown and totally isotropic with a refractive index lower than that of balsam. Small grains tested separately give indices varying widely from just below 1.500 to nearly 1.540; many grains lie close to 1.530 which may therefore be taken as a mean value. Within the chlorophaeite fine networks of minute cracks have developed; and occasionally incipient crystallization of the gel material has resulted in the development of minute fibres of an indeterminable birefringent mineral arranged in spherulitic fashion.

Closer study of the chlorophaeite disseminated through the rock shows that whereas some of the material occurs in quite irregular films indicating deposition from travelling solutions, much of it is present in areas with definitely rectangular outlines suggesting pyroxene pseudomorphs. As the brown monoclinic pyroxene in the rock is perfectly fresh the pseudomorphosed mineral must have been distinctly more susceptible to alteration than augite. Rhombic pyroxenes such as hypersthene are particularly unresistant to alteration, and the inference that the chlorophaeite pseudomorphs represent completely altered rhombic pyroxenes is fully in accord with the forms of the pseudomorphs and with the chemical composition of the rock to be given below.

CHEMICAL COMPOSITION. An analysis of the tachylytic phase of the dyke, free from chlorophaeite, gave the following values, from which was deduced the appended mineral constitution:

SiO ₂	48.90	Orthoclase.....	16.68
TiO ₂	1.86	Albite.....	16.77
Al ₂ O ₃	12.70	Anorthite.....	17.51
Fe ₂ O ₃	2.82	Diopside.....	24.52
FeO.....	12.93	Hypersthene.....	13.56
MnO.....	.73	Magnetite.....	4.18
MgO.....	2.65	Ilmenite.....	3.65
CaO.....	9.30	C. I. P. W. Symbol. III.	5.3.3.
Na ₂ O.....	1.97		
K ₂ O.....	2.83		
Ignition.....	3.11		
	99.80		

Tachylytic phase of trachydolerite, free from chlorophaeite; 55 foot dyke cutting Columbia River basalt, Grande Ronde Valley, just S. of the town of Anatone, S.E. Washington. Analysts, Ledoux & Co.

In the main the analysis and the derived mineral constitution accord well with the mode of the coarser rock described above. Potash, and consequently normative orthoclase, is surprisingly high; and as orthoclase was not found in the section it is evident that potash has partly entered the plagioclase molecule, and is partly occult in the groundmass. The low value for magnesia is unusual, and this constituent was therefore redetermined with concordant results. The ores are notably titaniferous, as expected, and the ferromagnesians are wholly metasilicates supporting the conclusion that the chlorophaeite pseudomorphs are replaced pyroxenes and not olivines. In view of the alkalic character of the feldspar and the relatively low silica-content this rock has been classed with the trachydolerites.

TABLE I. ANALYSES OF CHLOROPHAEITE

	I	II	III	IV
SiO ₂	38.67	36.00	32.95	35.15
TiO ₂	0.24	.....	0.62	.....
Al ₂ O ₃	1.54	.....	5.40	1.00
Fe ₂ O ₃	26.14	22.80	12.37	21.77
FeO.....	2.06	2.46	9.18	2.18
MnO.....	0.31	0.50	0.33	0.35
MgO.....	6.77	9.50	4.75	5.02
CaO.....	1.72	2.52	3.05	2.51
Na ₂ O.....	0.00	} trace	1.68	} trace
K ₂ O.....	0.10		0.36	
H ₂ O+.....	9.56	7.23	5.20	4.98
H ₂ O-.....	12.54	19.23	23.90	27.44
	<hr/>	<hr/>	<hr/>	<hr/>
	99.65	100.24	99.79	100.40
G.....	2.267	2.020	1.81 ±	1.83-84

I. Grande Ronde Valley, near Anatone, S. E. Washington. Analysts, Ledoux & Co.

II. Sgurr Mor, Rum, Scotland (type locality). Analyst, M. F. Heddle. Ref. Heddle, 1880, p. 87.

III. Ravelrig Quarry, Dalmahoy near Edinburgh, Scotland. Analyst, W. H. Herdsman. Ref. Campbell and Lunn, 1925, p. 438.

IV. Nagpur, India. Analyst, B. P. C. Roy. Ref. Fermor, 1925, p. 127.

In TABLE I is given an analysis of clean fragments of the amygdale-filling chlorophaeite from the Grande Ronde dyke together with Heddle's analysis of the type material from Rum,

Scotland, and two recent analyses of chlorophaeite from Scotland and India respectively. These represent all the available chemical data of reliable quality. The new analysis exhibits the characteristic features of the previous ones. Water is a large component, and the bulk of it is liberated at 100°. Ferric oxide is also large and strongly dominant over ferrous oxide. Alumina and the divalent bases are subordinate, and the alkalis are vanishingly small.

A complex gel-mineral cannot, of course, be expected to yield a definite constant molecular formula; in TABLE II, however, an attempt is made to derive a general molecular expression which will approximately embrace the four analyses. In a hydrous, amorphous mineral a distinction between combined and hygroscopic water does not exist; therefore total water has been included in the derived formula.

TABLE II. MOLECULAR CONSTITUTION OF CHLOROPHAEITE

	Grande Ronde	Rum	Dalmahoy	Nagpur	Average
SiO ₂	.645	.600	.549	.586	.586
TiO ₂	.003	....	.008	....
Al ₂ O ₃	.015	....	.053	.010	.146
Fe ₂ O ₃	.163	.142	.078	.136	
FeO	.029	.034	.128	.031	.206
MnO	.004	.007	.004	.005	
MgO	.169	.237	.119	.125	.275 = 2(.138)
CaO	.030	.045	.055	.045	
Na ₂ O	.000	.000	.027	.000	1.801
K ₂ O	.001	.000	.004	.000	
H ₂ O+	.531	.402	.289	.277	1.529 = 10(.153)
H ₂ O-	.697	1.068	1.328	1.524	

From these figures we obtain the expression: $R_2O_3 \cdot 2(R,R_2)O \cdot 4SiO_2 + 10H_2O$, with some constancy of factors in the average column; or, neglecting TiO₂, MnO and the alkalis, and grouping the bases of similar valencies in order of decreasing abundance: $(Fe,Al)_2O_3 \cdot 2(Mg,Fe,Ca)O \cdot 4SiO_2 + 10H_2O$. Considering the nature of the material the four analyses conform to this formula reasonably well.³

THE IDENTITY OF CHLOROPHAEITE AND CERTAIN MATERIALS DESCRIBED AS PALAGONITE. In 1887 McMahon observed an

³ Professor Larsen has drawn our attention to the similarity between the composition of chlorophaeite and that of hisingerite, a hydrated ferric silicate found associated with pyrites.

abundant isotropic or feebly birefringent, orange-colored substance in "ball trap" from the Deccan. Of this material and a similar associated green substance McMahon wrote: "On the whole, then, I have come to the conclusion that the bright-orange and dull-green substances represent the original magma or glassy base of the rock" (1887, p. 108).

Two years later Middlemiss redescribed material similar to that studied by McMahon, and closed his paper thus: "In conclusion, I would state that though I consider these substances described in this paper as undoubtedly belonging to what has been called palagonite, I would not absolutely bind myself to the view either that they are metamorphosed or zeolitized portions of the original glassy magma (though I lean to this view), or that they are pseudomorphs after olivine" (1889, p. 234).

In 1916 Fermor and Fox described abundant shot-like spherules of glassy aspect in basalt from the Deccan, and suggested that the material is either identical or very similar to the chlorophaeite of MacCulloch (1916, p. 95). They also observed that much of the material was formed at the expense of the augite in the rock.

In 1925 Fermor described and discussed in detail palagonitic materials in specimens from the core of a deep boring through Deccan trap at Bhusawal. Observing that the description and illustrations of Middlemiss would apply closely to the Bhusawal material, Fermor follows Middlemiss in his use of palagonite as a comprehensive term denoting brown and green, mostly isotropic, hydrous materials of secondary origin. After careful study Fermor concludes, however, that the brown and orange varieties of palagonite are identical with chlorophaeite (1925, pp. 125, 130-131); and that the green variety, when anisotropic, is very probably delessite or celadonite (1925, p. 133). Just as in the present instance the Indian chlorophaeite, delessite and celadonite occur both in vesicles and distributed through the body of the rock; and Fermor concludes that while the major portion of these materials has been formed by hydration at the expense of the original glass of the rock, augite, olivine and iron-ores have contributed to their formation.

In the same year Wadia described a palagonite-dolerite from Nagpur, the type locality for Indian chlorophaeite. Wadia's material occurs in shot-like spherules and amoebiform chambers in the dolerite, and has clearly been formed at the expense of augite

in the rock (1925, pl. ii). As the material described by Wadia does not exhibit the color change shown by chlorophaeite, and occurs only to a minor extent as true vesicle-fillings, Wadia named his material palagonite in preference to chlorophaeite.

Also in 1925 Campbell and Lunn reported typical chlorophaeite in the dolerites (tholeiites) of Dalmahoy and Kaimes Hills near Edinburgh. This material occurs in vesicular patches, in veins, in association with areas of intersertal mesostasis, and pseudomorphic after olivine (1925, p. 436).

The following year one of us (Peacock) adopting the current usage, described and figured as a palagonite-olivine-dolerite a rather coarse-grained basic intrusive rock forming a massive sill on the island of Videy, near Reykjavík, Iceland (1926 A, pp. 457-458, fig. 9). In this rock the palagonitic material occurs in irregular areas some of which appear to be altered vitreous mesostasis, while others are undoubtedly altered olivine. Later in the same year the same author completed a study of the palagonite tuffs of Iceland, the type locality for palagonite, and arrived at a definite conception of the properties of the material to which Sartorius von Waltershausen gave the name palagonite. For reasons to be developed later the writer regarded the application of the term palagonite to the chlorophaeite-like bodies under discussion as undesirable and recommended that the usage be discontinued (1926 B, pp. 72-74).

From these brief excerpts it will be clear that chlorophaeite and the brown or orange-colored palagonitic materials in basalts and dolerites are either identical, or so closely similar that to sustain a distinction is impracticable. Indeed the only points of difference appear to be: first, that the palagonitic material in dolerites sometimes does not exhibit the color change of chlorophaeite; and second, that much of the palagonitic material occurs in the body of the rock, and not in true vesicles. Although the color change of chlorophaeite is a useful field characteristic, and is given special importance in the name itself, the systematic significance of the change appears to be rather trifling. Of the several attempts which have been made to ascertain the cause of the color change that of Campbell and Lunn seems to have been the most successful. These authors were able to inhibit the change from green to brown by placing the freshly broken material in an atmosphere of carbon dioxide, thus indicating that surface oxidation was concerned in

the change (1925, p. 439). The green condition is thus a very unstable phase of a typically brown material; and therefore, if a material shows all the properties of chlorophaeite except the color-change on fresh exposure, this change has undoubtedly already been undergone due to oxidizing conditions, and it seems unreasonable not to admit such a material as chlorophaeite, especially as all the data of chlorophaeite have of necessity been obtained from exposed material.

Again, the second distinction emphasized by Wadia, is unreal. While chlorophaeite occurs conspicuously in cavity-fillings the available descriptions of indisputable chlorophaeite all contain references to the occurrence of the material in the body of the rock. Indeed, so consistently has chlorophaeite been formed at the expense of pyroxene or olivine, or at the cost of the basic constituents of the mesostasis or vitreous base of the rocks in which it occurs, that we incline strongly to the belief that the chlorophaeite forming the conspicuous shot-like spherules in the hand-specimens has been formed by late-magmatic hydrothermal action on the basic constituents of the rock resulting in the production of a fluid product which intimately penetrated the rock and was deposited in cavities if such existed.

Our material contains the green phase only in small amount; in thin section it is partly isotropic and partly individualized as birefringent chloritic fibres. Campbell and Lunn unhesitatingly class their green isotropic material as chlorophaeite, and in view of the green color exhibited by perfectly fresh chlorophaeite there can be no doubt that the green material represents areas of chlorophaeite which have escaped oxidation with the consequent color change to orange-brown.

We therefore conclude that both the green and the orange-brown isotropic materials may be properly classed as chlorophaeite, and that the term palagonite is thus free to describe the material for which it was designed, namely the hydro-gel of sideromelane.

DEFINITION OF CHLOROPHAEITE. A study of chlorophaeite from a new locality, together with a comparative examination of existing descriptions of chlorophaeite and of palagonitic materials differing from chlorophaeite in no essential respect, show that chlorophaeite, although somewhat variable in properties, is a well-recognized petrographic entity. While such a material cannot be classed as a mineral species in the strict sense, it falls properly

into the group of *mineraloids* proposed by Niedzwiedzki (1909, pp. 661-663) to embrace all naturally occurring, homogeneous, amorphous substances.

To conclude the discussion of chlorophaeite it may be of value to offer a condensed definitive description which will embrace authoritatively reported variations of this material.

Chlorophaeite, Macculloch, 1919, p. 506; derivation, *χλωρός*, *green*, and *φαίος*, *brown*. Color, deepest brown, or olive-green changing rapidly on exposure (oxidation) to deepest brown. Amorphous; no plane cleavage; fracture, conchoidal; lustre, jet-like, pitch-like, or dull; streak, brown; H. = $1\frac{1}{2}$ -3; G. = 1.81-2.23; infus.; gives dull black magnetic mass. Color in thin slices, pale-green, olive-green, orange-brown (commonest), red; isotropic; when birefringent, due to chloritic fibres; R.I. = 1.50-1.54. Chem. comp. approximating $(\text{Fe, Al})_2\text{O}_3 \cdot 2(\text{Mg, Fe, Ca})\text{O} \cdot 4\text{SiO}_2 + 10\text{H}_2\text{O}$; greater portion of H_2O liberated at 100° . Occurs in shot-like spherules up to 8 mm. diameter, filling or lining cavities, in amoebiform or irregular patches, in veinlets, pseudomorphic after olivine and pyroxene, and replacing vitreous base or mesostasis in basic extrusives or intrusives ranging from mugearite, trachydolerite, to basalt and olivine-dolerite. Origin, probably due to hydrothermal action on ferromagnesian minerals and on the basic constituents of the vitreous base or mesostasis, resulting in a fluid product which permeates the rock and is deposited in the various ways indicated. Localities, numerous in Scotland, also in England and Ireland (Campbell and Lunn, 1925, pp. 435 and 440, whom see for earlier refs. to British occurrences); Deccan Plateau (Fermor, 1925, pp. 125-135, whom see for earlier refs. to Indian occurrences); Iceland (Peacock, 1926 A, p. 458 and fig. 9; here named palagonite following usage now disapproved); Columbia River Plateau (this paper); Faeroe occurrence given by Dana discredited by Heddle (1880, p. 85).

SIDEROMELANE

OCCURRENCE. The example of sideromelane chosen for full description was taken from the nose of a basaltic flow at Columbia River, 3 miles S.W. of Moses Coulee, Douglas Co., central Washington. The field relations indicate that the flow entered a lake and consequently suffered drastic quenching.

HAND-SPECIMEN. The material consists of a number of irregularly shaped pieces of black basaltic glass, the largest unfractured piece being 4 cm. long. The individual pieces are bounded partly by somewhat rough surfaces which are parts of the original corded or ropy flow-surface of the lava; partly by smoother, curved and corroded surfaces representing original shrinkage fracture-surfaces along which volcanic vapors have slightly attacked the glass; and partly by fresh, hackly-conchoidal surfaces of vitreous lustre produced in detaching the material. The glass contains large, distorted steam-cavities reaching a length of 2 cm., and numerous minute vesicles. Apart from a slight development of white and rusty corrosion products along incipient cracks and in some of the steam-cavities, the glass appears homogeneous and perfectly fresh. Small fragments examined without a lens are translucent at thin edges, and the powdered material is faintly greenish, notably translucent, and similar to powdered bottle-glass in appearance. The powder gives no streak; the hardness of the glass is $5\frac{1}{2}$; and the specific gravity of a clean fragment about 1 cub. cm. in volume and sensibly free from vesicles is 2.74.

MICROSTUDY. Crushed samples temporarily mounted in standardized immersion liquids consist essentially of glass shards typically bounded by smooth, curved fracture-edges. In terms of Ridgway's *COLOR STANDARDS* (1912) these fragments range from "pale olive-buff" in the smallest pieces to "citrine drab" in the largest ones. Except for a few tabular microlites of sodic labradorite (ab:an=45:55) and of faintly colored rhombic and monoclinic pyroxene the glass is perfectly clear, fresh, homogeneous and isotropic with a refractive index of 1.583.

In addition to the dominant olive-buff shards a few colorless fragments and still fewer yellow fragments are seen. The colorless grains represent the white corrosion product already mentioned, and the yellow grains are probably related to the rusty films; both materials have the vitric structure of the fresh glass. The colorless material has acquired barely perceptible aggregate birefringence with marked reduction of refractive index to 1.44–1.45. The yellow grains are still perfectly isotropic with a refractive index similar to that of the fresh glass. From these characters and the appearance of the hand-specimens it is conjectured that the colorless fragments are essentially hydrated silica and alumina produced by the corrosive action of acidic volcanic vapors travelling along

fractures in the newly consolidated glass and removing the more soluble and strongly refringent components, principally iron and magnesia; and that the yellow particles are derived from surfaces of the fresh glass which have suffered no alteration beyond some hydration and oxidation.

CHEMICAL COMPOSITION

SiO ₂	51.30	Orthoclase.....	6.12
TiO ₂	1.40	Albite.....	24.10
Al ₂ O ₃	18.54	Anorthite.....	34.47
Fe ₂ O ₃	0.26	Diopside.....	6.80
FeO.....	11.21	Hypersthene.....	23.84
MnO.....	0.35	Olivine.....	1.06
MgO.....	4.03	Magnetite.....	0.46
CaO.....	8.55	Ilmenite.....	2.74
Na ₂ O.....	2.83		
K ₂ O.....	1.05	C.I.P.W. Symbol...II (III). 5. "4. 4.	
H ₂ O +.....	0.30		
H ₂ O -.....	trace		
P ₂ O ₅	0.05		
CO ₂	none		
S.....	none		
<hr/>			
99.87			

Sideromelane (Ideal Basaltic Glass), from the lake-quenched nose of a flow at Columbia River, 3 miles S.W. of Moses Coulee, Douglas Co., Washington. Analysts W. H. & F. Herdsman.

The analysis and mineral composition are those of a slightly undersaturated basalt. The only striking feature is the very low value for Fe₂O₃. Previous sideromelane analyses show the same feature (Peacock, 1926 B, p. 57), and thus a relation between the pale color and low tenor of ferric oxide suggests itself.

THE NOMENCLATURE OF BASIC GLASSES. Various terms have been proposed and employed to designate basaltic glasses and dominantly vitreous basalts. The older texts give the following: tachylyte⁴ (Breithaupt, 1826); hyalomelane (Hausmann, 1846); sideromelane (Sartorius von Waltershausen, 1853); basalt-obsidian (Cohen, 1880); and hyalobasalt (Rosenbusch, 1887). Breithaupt's original description of tachylyte (1826) is brief and lacks micro-

⁴ From *ταχύς*, *quick*, and, *λυτός*, *dissolved*, in the sense of *fused*. The second "y" in tachylyte being thus demanded by the derivation, the spelling tachylyte is not recommended.

scopical criteria. The material occurs in basalt at Säsebühl between Dransfeld and Göttingen; it is described as opaque, similar to obsidian, and readily fusible, this last property being expressed in the name. In 1847 Hausmann distinguished the basaltic glass from Bobenhausen with the name hyalomelane although even then the grounds for the distinction were not apparent. In 1872 Rosenbusch (1872, p. 147) suggested the arbitrary separation of basaltic glasses according to their solubility in HCl, and proposed that tachylite be reserved for glasses soluble with some readiness, and hyalomelane for insoluble glasses. But this distinction attached the meaning "rapidly soluble" to the word tachylite, which was not intended by Breithaupt, and classed as insoluble the Bobenhausen material which is in fact more soluble. Penck was inclined to attach little weight to this distinction (1879, p. 521), and Judd and Cole clearly showed that "the supposed distinction between tachylite and hyalomelane, founded on their behavior with acids, altogether fails in practice as a means of discrimination between the different varieties" (1883, p. 461). Rosenbusch, however, had already abandoned the solubility-distinction (1877, p. 445), and the term hyalomelane has since become obsolete.

In 1853 Sartorius von Waltershausen described as sideromelane⁶ basaltic, vitreous chips in the palagonite-tuffs of Sicily and Iceland. The following properties were given: color, lustre and fracture, like obsidian; hardness barely that of labradorite; sp. gr. 2.531; dull-black on weathered surfaces; amorphous, without trace of outward form or cleavage; wholly dissolved in warm, concentrated HCl; composition similar to basalt (1853, pp. 202-204). In their report on the basic volcanic material dredged from the bottom of the Pacific Ocean during the voyage of H. M. S. "CHALLENGER" Murray and Renard described and figured fragments of fresh, basaltic glass from the nuclei of manganese nodules; this glass is clear and olive-buff in color in thin sections, and carries only a small microlitic content composed of olivine and plagioclase (1891, pp. 299-311, pls. xvi, xvii). The authors identified this material with the sideromelane of von Waltershausen. In a recent study of the basic tuffs of Iceland one of us (Peacock) found that fragments of fresh, basaltic glass, pale apple-green in thin sections and precisely similar to the "CHALLENGER" material, form an im-

⁶ Sideromelan in German. In English sideromelane is preferred and used throughout the paper.

portant component of the tuffs of Glacial and Recent Age (1926 B, pp. 56-60, pl. i). As this material contrasts so strikingly with the deep-brown, almost opaque appearance of thin sections from the tachylytic margins of basic intrusive bodies; and as, furthermore, this difference between the two types of basaltic glass seems to be directly related to the different cooling conditions attending their formation, it was deemed desirable to revive von Waltershausen's obsolescent term *sideromelane* to denote the rather uncommon, clear, pale-colored basaltic glass produced by drastic chilling of basalt magma (subglacial extrusion in Iceland, and submarine eruption in the case of the shell-bearing tuffs of Sicily and the non-pumiceous deep-sea examples), as distinct from the less rapidly chilled vitreous selvages of basaltic intrusions which are typically deep-brown or nearly opaque in thin sections due to incipient or advanced separation of turgid or opaque bodies consisting mainly of magnetite. As a sufficiently distinct petrographic entity it was further suggested that *sideromelane* might be classed with the mineraloids of Niedzwiedzki⁶ (Peacock, 1926 B, pp. 66-67).

Our attention has been drawn to the fact that the standard lexicons identify tachylyte with basalt glass; and as *sideromelane* is simply ideal basalt glass the question of the validity of von Waltershausen's term is reopened. An examination of all the descriptions of analyzed basaltic glasses collected by Washington (1917) and listed under the rock names chosen by the respective authors, and of some further relevant descriptions, shows however that with only one exception tachylyte has been used consistently and exclusively to describe deep-brown, turgid, dohyaline, chilled selvages of basic intrusive bodies; and that basalt glass has invariably been reserved for the pale-colored, clear material forming surface films on rapidly cooled lavas and occurring in small and consequently quickly chilled fragmental basaltic ejecta. To describe *sideromelane* as tachylyte would thus be misleading; and to describe it simply as basalt glass would, through the nominal identity of tachylyte and basalt glass given in the works of reference, lead to the same misconception. And therefore, while admitting the necessity of reducing nomenclature to a working minimum, we believe that there is still room for *sideromelane* as a specific name to denote ideal basaltic glass.

⁶ Adopting Niedzwiedzki's definition of mineraloid, Rogers had already urged that natural glasses be classed as mineraloids (1917, p. 540).

FURTHER OCCURRENCES OF SIDEROMELANE. The specimen of sideromelane described represents the less common occurrence of this type of glass in coherent masses of some size. In our material sideromelane appears also as a thin film on the surface of a slaggy basalt from the Jordan Craters, 20 miles N. of Jordan Valley, Malheur County, Oregon; in a fresh, fragmental condition as the principal constituent of sideromelane breccias and tuffs; and in variously altered fragmental conditions in palagonitic tuffs.

A breccia associated with the end of the flow from which the typical sideromelane was collected, at Columbia River, 3 miles S.W. of Moses Coulee, Central Washington, consists essentially of black angular fragments of sideromelane cemented with abundant calcite. Examined in small grains the sideromelane is seen to be perfectly fresh except for a very slight development of the colorless and yellow corrosion products previously described.

A specimen from the top of Asotin Crater No. 2,⁷ Asotin, Washington, consists wholly of lightly-cohering fragments of sideromelane averaging about 2 mm. in diameter; the rock is almost identical to granulated slag in appearance. In thin section the sideromelane is pale brown and perfectly fresh. It carries a subordinate amount of olivine and calcic plagioclase phenocrysts which together with a refractive index of 1.597 indicates a more basic composition than that of the type sideromelane chosen for full description.

In the remaining specimens sideromelane is variously altered; the treatment of these altered sideromelane tuffs falls properly into the next section.

PALAGONITE

PETROGRAPHIC DESCRIPTIONS. In the present material the rock most closely approximating to a typical Icelandic palagonite-tuff is a specimen of "Asotin Sandstone" from the southern margin of Asotin Crater No. 12, 1½ miles north of Asotin, on the Washington side of the Snake River. The hand-specimen is a fine-grained, earthy-brown, friable rock in which a few specks of fresh black sideromelane can be discerned embedded in an abundant brown material of similar grain-size. In thin section the rock is seen to

⁷ The geological relations and volcanic mechanism of the Asotin Craters of the Columbia River basalt have recently been described by one of us (Fuller, 1928); and the craters have been given numbers (fig. 1) which are used in the present paper.

consist of olive-buff fragments of sideromelane averaging 0.5 mm. in diameter and carrying a small proportion of pyroxene and plagioclase microlites. Internally the sideromelane fragments are perfectly fresh with a refractive index of 1.592; marginally each grain is converted into yellow palagonite with a low and variable refractive index of 1.47 ± 0.01 . A small amount of the yellow palagonite is clear and isotropic, and thus exactly like the ideal "gel-palagonite" found to a limited extent in those Icelandic palagonite-tuffs in which sideromelane has suffered hydration by immersion in sea-water. The greater proportion of the palagonite margins is slightly turgid and birefringent due to incipient separation of some opaque mineral, and incipient molecular organization of the gel in obscure, fibrous, spherulitic or vermicular fashion. In this condition specific determination of the minerals commencing to separate from the gel is quite impracticable; and the obscurely birefracting palagonite is thus identical with the "fibro-palagonite" commonly found in those Icelandic tuffs which have suffered hydration at rather higher temperatures in the neighborhood of hot springs.

In the study of the Icelandic tuffs already cited it was found that the refractive index and water-content of palagonite are related roughly in an inverse linear manner (Peacock, 1926 B, p. 70 and fig. 4); in the present case, knowing the refractive index of the fresh sideromelane (1.59), of the palagonite (1.47), and of water (1.33), the water-content of the palagonite is found to be about 32 per cent. as against 28 per cent. in the most hydrated Icelandic example.

In the Icelandic palagonite-tuffs there is good evidence to show that yellow gel- and fibro-palagonite result simply from the hydration of sideromelane, this hydration being accompanied by extensive oxidation of the iron-content and some loss of lime and soda. In the present material yellow palagonite is too slightly represented to permit separation and chemical analysis; the microscopic similarity between the yellow palagonite from the Columbia River Plateau and from Iceland is so close, however, that we may infer with some assurance that the nature of the palagonitization process has been the same in both cases.

In the remaining specimens sideromelane has suffered more profound alteration. A coarse, lake-quenched breccia from Moses Coulee, about 1 mile south of Douglas Creek, Washington, con-

sists of sideromelane fragments embedded in a rusty-white, earthy matrix. In thin section this matrix is seen to consist of small sideromelane fragments wholly converted into a turgid-gray substance, almost isotropic, with a refractive index of 1.45 ± 0.01 . Around the borders of these altered sideromelane fragments, and sometimes within them, minute, colorless, fibrous, vermicular structures have developed; these are probably zeolitic in composition. Obscure chloritic and limonitic spots, representing greatly altered pyroxene microlites, are scattered through the altered glass.

A tuff from Asotin Crater No. 6 consists dominantly of earthy-gray, altered sideromelane dust. In the hand-specimen a quartz pebble 2 cm. long is seen embedded in the tuff and in the section several foreign quartz grains appear. The sideromelane fragments are somewhat vesicular, and the alteration to fibro-palagonite and to the turgid-gray product of severer alteration has taken place both around the fragments and within the steam cavities.

The last example, a white tuff⁸ from the base of Asotin Crater No. 2, consists almost wholly of sideromelane dust converted into the turgid-gray product of severer alteration. Plagioclase and pyroxene microlites have survived the alteration process with little change; abundant minute spots of iddingsite represent olivine microlites which have completely succumbed.

The very low refractive index (1.45) of the turgid-gray alteration product of sideromelane in the above three examples, and the absence of the yellow or brown color characteristic of palagonite formed under the usual mild conditions of hydration and oxidation, suggest that the turgid-gray material represents sideromelane which has suffered, in addition to hydration, a loss of iron and perhaps of other bases by solution. In Iceland hot-spring action is unable to produce so profound a change on sideromelane; and the conjecture, based on petrographic evidence, that the tuffs characterized by the turgid-gray material have been acted upon by acidic vapors, is supported by the field evidence which strongly indicates that the palagonitization of these tuffs was effected by the steam generated in the quenching of the extruded material.

⁸ This rock is to be distinguished from the "white tuff" recently described from the Asotin Craters by one of us (Fuller, 1928, p. 61). This white tuff consists of minute, pumiceous fragments which appear to have suffered a loss of iron by volatilization.

At the vents this steam would probably be charged with acidic volatiles. As such conditions differ from the normal, milder palagonitization conditions in degree rather than in kind, it seems necessary to extend the term palagonite to include the turgid-gray, probably iron-free product of severer alteration of sideromelane.

The present petrographic evidence thus again shows that palagonitization proceeds from hydration and alteration by water or water-vapor of exotic origin, while the formation of chlorophaeite is a deuteric process induced by endogenous fluids. This confirms the distinction between the two processes already stated by one of us in slightly different terms (Peacock, 1926 B, pp. 72-74).

THE USE OF THE TERM PALAGONITE. The term palagonite was applied by von Waltershausen in 1845⁹ to the material forming the brown groundmass of a tuff from Palagonia, Val di Noto, Sicily. The following properties were given: fully transparent; color, wine-yellow to resin-brown; lustre, vitreous; fracture, splintery-conchoidal; external appearance, like gum-arabic or brown sugar; hardness, slightly over 3; specific gravity, about 2.64; becomes opaque before the blowpipe and fuses readily to a black, lustrous, magnetic bead; soluble in HCl with residue of silica; contains 16 per cent. of water, also ferric oxide, silica and alumina (1845, pp. 402-403).

In 1846 von Waltershausen found palagonite typically developed and widely distributed in the tuffs of Iceland. At Seljadalur, near Reykjavík, he recognized a massive tuff-bed partly composed of apparently pure palagonite; to this rock he gave the name *Palagonitfels* (1847, pp. 76-79).

Although von Waltershausen's writings on palagonite are voluminous and somewhat obscured by now discarded mineralogical theory, a clear conception of what this author understood by palagonite and the manner in which he used the term can readily be gained from his three publications on the subject (1845, 1847, 1853). Firstly, palagonite was claimed as a new mineral species (1845, p. 402). Secondly, the common structural relation of palagonite to sideromelane was clearly appreciated.¹⁰ Thirdly, it was

⁹ The extract: "ein neues. . . . Mineral, dem ich den Namen Palagonit beigelegt habe" (1845, p. 402), indicates that the name was actually proposed at an earlier date. No earlier reference, however, was found.

¹⁰ Auf den Verwitterungsflächen . . . kommt der Sideromelan, vom Palagonit umhüllt, sehr deutlich zum Vorschein, . . . (1853, p. 203).

shown by analyses that palagonite is hydrated sideromelane.¹¹ And fourthly, by the frequent use of *Palagonittuff* and *Palagonitfels* it is clear that palagonite was used as a mineral qualifier and not as a rock name.

On the grounds that von Waltershausen's *Palagonitfels* proved to be an aggregate of fragments of sideromelane together with their alteration products Penck concluded: "dass ein als Palagonit zu bezeichnender Körper nicht existirt" (1879, p. 568); and thereafter, having been discredited as a mineral species, palagonite was variously used, sometimes as a synonym for palagonite-tuff, and sometimes to denote any altered basic glass. Murray and Renard, however, in their description of the palagonitic materials dredged by the "CHALLENGER," adhered strictly to von Waltershausen's original usage (1891, pp. 299-311).

A recent study of the basic tuffs of Iceland by one of us served substantially to corroborate von Waltershausen's views on the nature and origin of palagonite, and to support his usage of the term. It was found that palagonite is a well-individualized material, not a mineral, of course, in the present restricted sense, but a mineraloid in the sense of Niedzwiedzki; and that palagonite was invariably formed by the hydration of sideromelane, this hydration being accompanied by extensive oxidation of the iron-content and by some loss of lime and soda. It was furthermore suggested, in accordance with the original usage, that palagonitic tuff, palagonite-tuff and palagonite-rock be used to denote palagonitized sideromelane-tuffs according to the extent to which they had suffered alteration by hydration. And finally it was recommended that the use of palagonite to denote certain chlorophaeite-like bodies in some basalts and dolerites be discontinued (Peacock, 1926 B, pp. 56, 72-74). From a study of the present material it was found desirable to include under palagonite the turgid-gray material representing sideromelane which had undergone somewhat more intense alteration than that which affected sideromelane in the Icelandic tuffs; but beyond this, no reason has appeared for departing from the standpoint outlined above.

In a critical discussion of this standpoint expressed in a personal

¹¹ In Folge der mitgetheilten Beobachtungen steht es daher fest, dass dieser Palagonit . . . aus Sideromelan entstanden sei, dem 3 Atome Wasser hingefügt sind, . . . (1853, p. 213).

communication¹² Dr. L. L. Fermor urges that chlorophaeite and Icelandic gel-palagonite are identical on the basis of chemical composition and optical properties; that therefore the later term palagonite should be dropped as a mineral term; that palagonitization be retained for the process whereby basic glasses become hydrated; and that palagonite be retained as a rock name to signify basic glass together with hydration and other alteration products.

In the following table the values for the sesquioxides and ferrous oxide in chlorophaeite and palagonite are contrasted.

TABLE III.

	Chlorophaeite	Palagonite		
	I	II	III	IV
Al ₂ O ₃	3.6	11.2	16.26	14.64
Fe ₂ O ₃	20.1	10.3	14.57	7.93
FeO	5.7	2.2	.....	0.87

I. Average of six analyses, including two materials named palagonite, respectively from Franz Josef Land (Teall, 1897, p. 485), and Massachusetts (Emerson, 1905, p. 112), but differing from chlorophaeite in no essential respect.

II. Palagonite-rock, Iceland; representing gel-palagonite closely enough for the present purpose (Peacock, 1926 B, p. 66).

III. Palagonite, South Pacific (Murray and Renard, 1891, p. 307).

IV. Palagonitic tuff, Eden Islet, Galápagos Islands (Washington and Keyes, 1927, p. 541).

In chlorophaeite ferric oxide is strongly dominant and alumina is almost negligible; in palagonite, on the other hand, ferric oxide and alumina are present in comparable amounts by weight. In a general formula, where the sesquioxides are grouped together, this difference would not appear; and normally, such a difference is regarded as insignificant. But in the present case the strong dominance of ferric oxide in chlorophaeite and the abundance of alumina in palagonite seem to be of genetic significance. In every case chlorophaeite has apparently resulted from the action of hydrothermal solutions on olivine or pyroxene, or on the basic constituents of the vitreous groundmass of basalts or dolerites; the product of this action is thus naturally rich in iron and poor

¹² Calcutta, September, 1927. As Dr. Fermor expresses the intention of including the argument contained in this letter in a forthcoming paper in the Records of the Geological Survey of India we feel free to discuss here the questions raised.

in alumina. In palagonite, however, which results from the hydration of sideromelane, a concentration of iron or an elimination of alumina are not to be expected. Indeed the present material indicates that extreme palagonitization is actually accompanied by removal of iron. We believe, therefore, that a chemical distinction of genetic significance exists between chlorophaeite and palagonite; and thus we are unable to follow Dr. Fermor's recommendations based on their contended identity.

The difficulties attending the application of the terms chlorophaeite and palagonite seem to vanish if the definition of chlorophaeite be slightly extended, as already suggested, to embrace all those hydrous, amorphous, pitch-like materials in basalts or dolerites, whether they show the green to brown color-change or not; and palagonite be restricted to its original significance, namely the hydration product of sideromelane, by water or water vapor of exotic origin, found typically in dohyaline pyroclastics of basic composition. This distinction is based primarily not on mode of occurrence, but on a chemical difference dependent on mode of occurrence, which may therefore be taken as a reliable indirect means of distinguishing between the two materials.

Mineraloids of closely similar properties have been separated on the basis of important differences in mode of occurrence; Fermor, for example, follows Heddle and Lacroix in distinguishing between celadonite and glauconite on such a basis (1925, p. 142). With their highly distinctive megascopic and modes of origin chlorophaeite and palagonite are in no danger of confusion from the field standpoint. And therefore in view of the optical and chemical differences which in addition exist between them, we feel that the definite separation of these two basaltic mineraloids is rigorously demanded.

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FIG. 1



FIG. 2

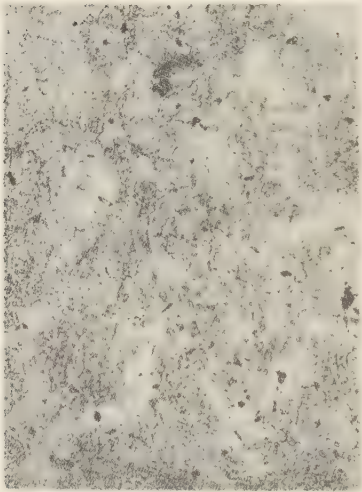


FIG. 3

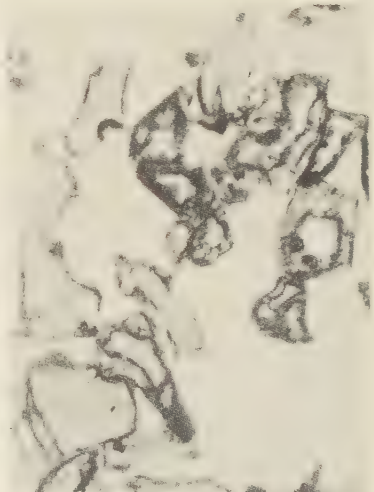


FIG. 4

EXPLANATION OF PLATE XII

Fig. 1. Thin section of sideromelane (ideal basaltic glass), from the chilled nose of a basaltic flow at Columbia River, 3 miles S.W. of Moses Coulee, Washington. The glass is olive-buff in color, and carries microlites of pyroxene and labradorite. (69 diameters.)

Fig. 2. Thin section of tachylyte from the chilled margin of a basaltic dyke at Torvaig, Portree, Skye, Scotland. This is a deep-brown glass rendered largely opaque due to separation of magnetite. The specimen is a gift from Dr. Alfred Harker. (69 diameters.)

Fig. 3. Thin section of chlorophaeite in an amygdale in a trachydolerite dyke cutting Columbia River basalt in the Grande Ronde valley, just S. of Anatone, Washington. The material is orange-brown and isotropic, and is traversed by a network of fine curved cracks such as would be produced in the shrinking of a rigid gel. (159 diameters.)

Fig. 4. Thin section of palagonite-tuff from Asotin Crater No. 12 (Fuller, 1928, fig. 1), $1\frac{1}{2}$ miles N. of Asotin, Washington. The rock consists of sideromelane fragments converted marginally, by hydration, into palagonite. Some of this is clear, yellow, isotropic gel-palagonite; the bulk of it is turgid, obscurely birefringent fibro-palagonite. (69 diameters.)

Photomicrographs by M. A. P. Multiply the above magnifications by $\frac{1}{2}$.

ZIRCON FROM NORTH BURGESS, ONTARIO

CHARLES PALACHE AND H. V. ELLSWORTH

Although no mineral has been longer the subject of exact studies than zircon, there is a notable lack in the literature of investigations of its various properties made upon material from any single locality. A large suite of specimens recently secured by the Harvard Mineralogical Museum seemed to offer unusual opportunity for such a series of studies and although not exhaustive, the following data have the merit of being secured from homogeneous material from a single deposit.

Mr. W. F. Ferrier, through whom the zircon was obtained for the Museum, has supplied data on its place and mode of occurrence secured from Mr. W. L. McLaren of Perth, Ontario, who collected the zircons when operating mica mines in 1904 and 1905. The locality is near Otty Lake in the township of North Burgess, Lanark Co., Ontario, about four miles directly south of Perth.



Fig. 1. Map of the locality in North Burgess, Ont., where zircon was found.

The detail map,¹ figure 1, shows the two pits from which the zircons came; they lie among scores of similar openings, originally

¹ Drawn from the map in an article by H. G. Vennor on Apatite Deposits of Lanark Co., in *Geol. Surv. Canada, Rep. of Prog.*, 1873-74, 128; and from notes by Mr. McLaren. The minerals of this region, except zircon, are also described in Mica, H. de Schmid, *Can. Dep. of Mines No. 118*, 178, 1912.

developed about 1870 as apatite mines, later reworked in part as mica mines, and now all abandoned. Most of the crystals were taken from the pit located in Concession VIII, Lot 4, known as the Sand Pit. The one matrix specimen from here consists largely of serpentinized pyroxene with some granular calcite and fragmentary crystals of apatite. Several matrix specimens from the Megantic Pit show fresher rock with coarse cleavages of calcite, crystals of pyrite and phlogopite and areas of much fractured green apatite. The zircon in both groups of specimens is identical in color and properties. In the collections are a few matrix specimens of zircon from South Burgess which look much like these, but the zircon proved not to have the abnormality of angles which is peculiar to the North Burgess crystals.

CRYSTALLOGRAPHY. The zircon crystals from North Burgess are mostly loose but a few are still enclosed in their matrix. Few are now intact but the matrix specimens show that they were all originally complete individuals with double terminations. They range in size from a few millimeters in diameter to a length of 3 cm. and a cross section of 2×1 cm. The color is a deep red brown and when unflawed they are transparent and of gem quality. Unfortunately the crystals have been more or less fractured while imbedded and are very fragile, many of them falling to pieces when the matrix is disturbed. The smaller crystals are, however, sound and because of their brilliant faces particularly well suited for measurement.

The measurement and drawings of the crystals are the work of Dr. M. A. Peacock. All of them show the forms $m(110)$, $p(111)$, $u(331)$ and $x(311)$ but with the utmost variation in the development of the individual forms so that there is endless variety in the detailed habit. Figure 2 reproduces a crystal of average development showing the irregularity in size and shape of the faces of each form. The less common forms $\zeta(113)$ and $v(221)$ were seen only on the two crystals reproduced in figures 3 and 4, respectively. The form (113) was first recorded by Hidden² on a crystal from North Burgess, possibly from this identical pit, but was not figured. It has since been recorded only once from an Italian occurrence. $v(221)$ is also a rare form for zircon.

The first measurements made on these crystals revealed in the polar angles of all forms a definite and very consistent deviation

² *Am. J. Sc.*, 29, 250, 1885.

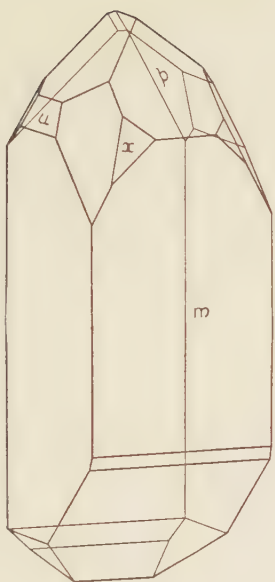
EXPLANATION OF PLATE XIII

Fig. 2. Zircon. Drawing of a crystal of average habit showing the forms $m(110)$, $p(111)$, $u(331)$, and $x(131)$.

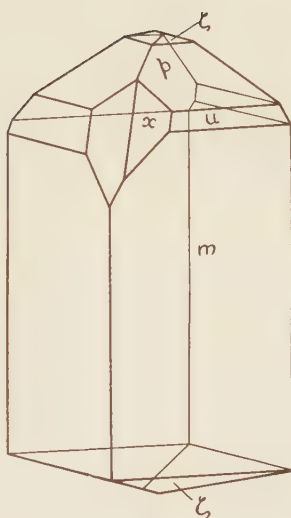
Fig. 3. Zircon. Drawing of an exceptional crystal showing the forms of figure 2 and in addition the uncommon pyramid $\zeta(113)$.

Fig. 4. Zircon. Drawing of a crystal of unusual habit showing the forms of figure 2 and in addition the rare pyramid $v(221)$.

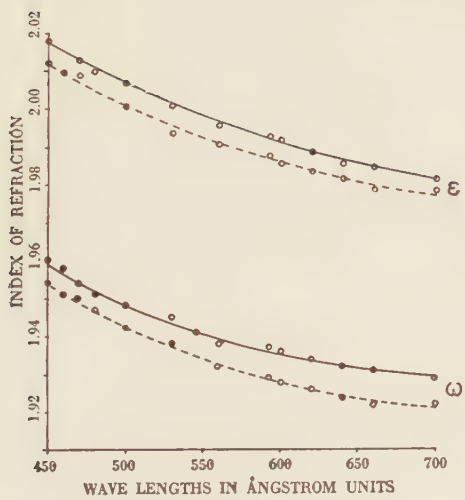
Fig. 5. Curve plotted from TABLE I showing indices of refraction and dispersion of zircon from North Burgess. Before heating ———. After heating



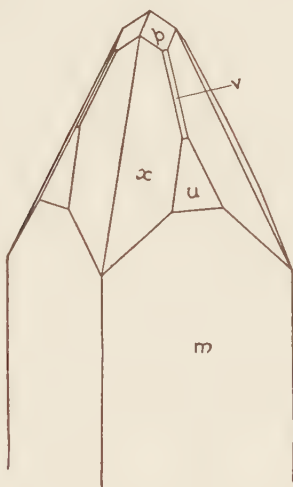
2



3



5



4

from the accepted values for zircon. This deviation proved to be characteristic and constant within rather narrow limits and seemed sufficiently notable to be investigated in the hope of finding some explanation for it in the chemical nature of the zircon. The angles obtained are shown in the following table. Only measurements of the best quality are included, obtained in every case without the use of the magnifying ocular.

Form	Measured		Deviations		Calculated
	ϕ	ρ	ϕ	ρ	$\bar{\rho}_0$
$p(111)$ Mean, 18 faces, 5 crystals	45°00'	42°16'	1'	+2 to -2'	.6427
Winkeltabellen	45 00	42 09 $\frac{2}{3}$			
$u(331)$ Mean, 7 faces, 2 crystals	45°00'	69 51	2	+2 to -2	.6424
Winkeltabellen	45 00	69 47 $\frac{1}{2}$			
$x(311)$ Mean, 24 faces, 5 crystals	18 26	63 49	3	+3 to -3	.6431
Winkeltabellen	18 26	63 43			3 \times .6432
Weighted average					.6429
Winkeltabellen					.6404

Poor readings were also obtained for the following:

		Calculated	
		ρ	ρ
$\xi(113)$	Mean 3 readings	16°56'	16°52'
$v(221)$	Mean 3 readings	61 09	61 11 $\frac{1}{2}$

The zircon crystals from North Burgess are completely de-colored by heating to a dull red heat for not more than one minute. To test the effect of this heating upon the angles, a crystal was measured before and after heating. It was found that the faces suffered a slight decrease of brilliancy but still gave excellent readings.

Before heating	After heating	Increase
ρ	ρ	
(111) 4 faces 42° 15' \pm 1'	42° 16' \pm 1'	1.0'
(331) 4 faces 69 49.8 \pm 2	69 51 \pm 2	1.2
(131) 8 faces 63 47.1 \pm 1	63 47.8 \pm 1	0.7

The permanent change of angular values is slight but definite and is consistent.

The angles calculated from the new element for these crystals are as follows:

	Calculated		Observed	Winkeltabellen
	ϕ	ρ	ρ	ρ
(111)	45°00'	42°16½'	42°16'	42°09¾'
(331)	45 00	69 52	69 51	69 47½
(131)	18 26	63 48½	63 49	63 43

(111)	ϕ 56° 48'30"	(Kupffer) 56°40'26"	Calculated	
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Thus the ρ angles of the three forms are from 5 to 6 minutes larger than the accepted values. That this variation is exceptional is shown by a careful examination of the observations recorded in Hintze. Calculating ρ from the observed angles where necessary and including all values apparently based on crystals of good quality we find the following:

OBSERVER	LOCALITY	FORM	ANGLE	ELEMENT	HfO ₂
			ρ	ρ_0	%
Kupffer	Ilmen Mts.	(111)	42°09'	.6404	1.1
Kokscharoff					
Dauber	Ceylon	(111)	42 10	.6404	...
Dauber	Pfitschthal	(111)	42 09	.6404	...
Dauber	Fredrikvarn	(111)	42 09	.6404	1.0
Vom Rath	Laach	(111)	42 10	.6404	...
Negri	Loreda	(111)	42 10	.6405	0.9
Artini	Novale	(111)	42 10	.6406	0.7
Lacroix	Espailly	(111)	42 10	.6406	0.7
Grattarola	Ceylon	(111)	42 10	.6407	...

One of the crystals from South Burgess mentioned above was measured and gave results which are fairly consistent and very close to normal values.

		ρ
(111)	4 faces	42°11' ± 2'
(331)	3 faces	69 45 ± 3'
(131)	5 faces	63 41 ± 6'

These angles vary not more than 2' from normal angles.

OPTICAL CHARACTERS. A prism was cut from one of the clearest crystals, the refracting edge being parallel to the *c*-axis, and the refracting angle, α , 20°31'. The measurements made upon this prism by Mr. Berman before and after heating are shown in the following table and in the plot, Plate XIII, figure 5. It is clear that the effect of heating which renders the substance colorless

is to lower the indices of refraction without, however, producing significant effect on the dispersion or birefringence. It is uniaxial both before and after heating.

TABLE I. INDICES OF REFRACTION OF ZIRCON FROM NORTH BURGESS

Wave length Ångstrom units	Before heating			After Heating		
	$\alpha=20^{\circ}31'$		Birefringence	$\alpha=20^{\circ}35'$		Birefringence
	ω	ϵ		ω	ϵ	
450	1.959	2.016	.057	1.953	2.011	.058
460	1.957	2.011	.054	1.950	2.008	.058
470	1.953	2.010	.058	1.949	2.007	.058
480	1.950	2.008	.058	1.946	2.003	.057
500	1.947	2.005	.059	1.941	1.999	.058
530	1.944	1.999	.055	1.937	1.992	.055
546	1.940	1.997	.057			
560	1.937	1.994	.057	1.931	1.989	.058
589	1.936	1.991	.055	1.928	1.986	.058
600	1.935	1.990	.055	1.927	1.984	.057
620	1.933	1.987	.054	1.925	1.982	.057
640	1.931	1.984	.053	1.923	1.980	.057
660	1.930	1.983	.053	1.921	1.977	.056
700	1.928	1.980	.052	1.921	1.977	.056

SPECIFIC GRAVITY. The specific gravity of the analyzed sample of North Burgess zircon (about 8 grams) was determined by Mr. Berman as 4.657 at 27° , and by Dr. Ellsworth as 4.659 at about 20° . A small portion of the same material after heating to dull redness had specific gravity 4.667 at 27° .

Another sample, the exact source of which in North Burgess is unknown, gave somewhat different values.

Specific gravity before heating 4.646

Specific gravity after heating 4.659

The increase in the two samples is of the same order.

CHEMICAL COMPOSITION. A sample of about 9 grams of the zircon was prepared by Mr. Berman. For this purpose a matrix specimen, probably from the Megantic Pit, was used, one of the crystals being measured to be sure that it had the characteristic large angles of the North Burgess material. The hand-picked fragments were found to have slight films of calcite, formed on some of the cracks in the otherwise glassy zircon; it was therefore treated with dilute HCl until effervescence ceased. Under the microscope no impurity could be discovered in the sample. The analysis was made by the junior author. The sample was crushed

on a hard steel plate, not ground, treated with HCl to remove particles of steel and sifted through silk. Solution was effected by 4 or 5 fusions alternating with alkali carbonate and bisulphate. The sample showed negligible radioactivity so that U and Th could not be determined by analytical methods. The procedure was such that Ti, Ta, Cb, Be, Mn and Sn should have been detected if present. Particular pains were taken to obtain the whole of the silica. Zirconia was precipitated by cupferron after removing Fe, Al, rare earths and alkaline earths.

ANALYSIS OF ZIRCON BY H. V. ELLSWORTH³

	Percentages	Mol. ratios
SiO ₂	32.51	.539
ZrO ₂	67.02	.544
CaO	0.22	.004
MgO	0.01	.....
Rare earths	0.04	.....
Fe ₂ O ₃	0.08	.0005
Al ₂ O ₃ , etc.	0.21	.002
Ignition	0.03	
	<hr/> 100.12	

The part played in the composition of zircon by the minor constituents shown above is unknown; in any case their amount is so small that their effect is almost negligible. If silica and zirconia alone be considered, the molecular ratios show a slight deficiency of silica. This might be regarded as due to the presence of hafnium oxide in the zirconia. If 1 per cent. of HfO₂ were considered to be present the one to one ratio of bases to silica would be exact.

	Percentages	Mol. wt.	Mol. ratios
SiO ₂	32.51	60.06	.541
ZrO ₂	65.52	123.	.537
HfO ₂	1.	210.6	.004
			} .541

It is known from the researches of Hevesy and others that some hafnium is always present in zircon. On page 388 above, in the last column of the table of previous observations made on zircon there are given the amounts of hafnium oxide determined in

³ Published by permission of the Director of the Geological Survey of Canada.

samples of zircon from several well known localities.⁴ In unaltered zircon (with measurable crystals) the amount seems not to exceed 1 per cent.

To test the hypothesis that hafnium oxide was present, the zirconia precipitate was examined in Professor Duane's laboratory at Harvard, for its Roentgen absorption spectrum. The result of this examination was negative as to the presence of hafnium. It is hoped, however, to have a more extensive examination of the mineral made for hafnium in the laboratory of Professor von Hevesy.

SUMMARY. Zircon crystals from North Burgess, Ontario, are characterized by unusual brilliancy; by extraordinary constancy of angles, corresponding faces on any one crystal never varying in position by more than one minute; by larger angles than hitherto recorded for the species, the polar angles of all forms being from five to six minutes larger than the accepted values; these angles lead to an axial ratio of $a:c=1: .6429$. The angles are increased by about one minute after heating to redness, a temperature which changes the red color to pure white. It is uniaxial, with the refractive indices of "normal zircon" and the indices are slightly lower after heating. The specific gravity, 4.646-4.658 is increased by heating to 4.659-4.667. Analysis shows it to be very pure zirconium silicate with an inconsiderable content of hafnium. The abnormal angles cannot therefore be assigned to the presence of the latter element and are unexplained.

⁴ von Hevesy, G. Recherches sur les Propriétés du Hafnium Kgl. Danske Vid. Selsk. Med., VI, 7, 25, 1925.

von Hevesy, G. DAS ELEMENT HAFNIUM, Berlin, 38, 1927.

BERYLLONITE AND OTHER PHOSPHATES FROM
NEWRY, MAINE

CHARLES PALACHE AND EARL V. SHANNON

The Dunton tourmaline mine in the town of Newry, Maine, was operated about twenty years ago in a search for gem tourmaline. The locality is described briefly by Bastin¹ and was widely known because of the large tourmalines found there with green center and pink border zone, tightly frozen in the pegmatite ledge-matter. Little gem tourmaline was found and the mine was soon abandoned.

This ledge and others near it was reopened in the summers of 1926 and 1927 under the superintendence of W. D. Nevel of Andover, Maine, in search for pollucite in commercial quantities.² The search was successful but mining has now ceased. Mr. Nevel saved with great care all unusual minerals found in opening these ledges and from him a very full suite has been secured for the Harvard Mineralogical Museum. On a later occasion it is hoped to give a full account of the paragenesis of this lithium pegmatite. In this paper it is intended to describe only three rare phosphates found there of which analyses have been made for the author by Dr. E. V. Shannon.

BERYLLONITE. Beryllonite was first described by E. S. Dana and H. L. Wells³ from Stoneham, Maine. Their material consisted of isolated crystals found by Sumner Andrews in the talus slope of a cliff together with other typical pegmatite minerals. Only one or two specimens showed the new mineral attached to any other substance and one of these, a smoky quartz crystal with a beryllonite crystal partly imbedded in it, is in the Harvard Mineralogical Museum. This ledge was never found in place and the whole pegmatite body appeared to have been undermined and disintegrated during the erosion of the valley. No other occurrence of this mineral has since been found. It was therefore with peculiar interest that the author, assisted by the optical data obtained by Mr. Berman, recognized beryllonite among some specimens sent in by Mr. Nevel for identification. A large suite of specimens has

¹ *Geology of the Pegmatites and Associated Rock of Maine, U. S. Geological Survey, Bull.* 445, 76, 1911.

² The Importance of Pollucite. E. E. Fairbanks, *Am. Mineral.*, 13, 21, 1928.

³ Description of the New Mineral Beryllonite, *Am. J. Sc.*, 37, 23, 1888.

now been examined and the description that follows is based upon them. The crystals are all more or less altered, the change ranging from a thin surface deposit of fibrous herderite, described on a later page, to the complete destruction of the beryllonite substance leaving a cavernous pseudomorph. The substance when fresh is snow white and shows perfect basal cleavage and less perfect orthopinacoidal cleavage. The alteration attack develops a fibration parallel to the vertical axis. No crystallographic measurements are possible on the coated crystals. They are thick, tabular parallel to the base, like the type beryllonite crystals, and there are some evidences of prismatic twinning. The largest crystal is far larger than any of Dana's crystals, reaching dimensions of 8×5 cm. in cross section and 4 cm. parallel to the vertical axis, while several are nearly as large in cross section and much thinner. The crystals are rarely attached to the walls of cavities; more commonly they are imbedded in albite of the platy clevelandite type, with rather vague outlines. It is the oldest of the phosphates to form, being coated with herderite, the product of its alteration, and in one specimen cut by a later crystal of eosphorite. Green tourmaline is in several specimens imbedded in the beryllonite and is apparently older.

Mr. Berman determined the specific gravity of the Newry beryllonite with the pycnometer to be 2.806. As this was much lower than the figure given by Dana, 2.845, three crystals from Stoneham were reexamined and gave values ranging from 2.791 to 2.808, an average of 2.798. It would appear that the true specific gravity of beryllonite is very near 2.80 and no explanation of the discrepancy between Berman's values and that of Dana was discovered.

The optical characters, practically identical with those given in Larsen's Tables, are as follows:

$$\begin{array}{ll} \text{Biaxial negative} & 2V \text{ medium} \\ \beta = 1.558 & \gamma = 1.562 \end{array}$$

Material for analysis was purified by Mr. Berman and proved under the microscope to be homogenous except for numerous fluid inclusions similar to those present in the Stoneham beryllonite.

The analysis by Dr. Shannon is as follows:

	PERCENTAGES	MOLECULAR RATIOS
BeO	19.12	.762
CaO	0.40	.007
MgO	trace	
Na ₂ O	23.28	.375
K ₂ O	0.92	.010
Li ₂ O	0.07	.002
P ₂ O ₅	55.40	.390
Al ₂ O ₃	0.21	
Fe ₂ O ₃	0.07	
Ignition	0.52	
Insoluble	0.16	
	<hr/> 100.15	

These results give with great exactness the same formula as did the type material, Na Be PO₄. It is worthy of note that small amounts of sodium are replaced by potassium and lithium. It is possible that the small amount of CaO found is derived from a slight admixture of herderite but the quantity is inconsiderable.

HERDERITE. Crystals of herderite have been found in a number of Maine lithium pegmatites and it is a far more common mineral than beryllonite, the only other known beryllium phosphate. At Newry, however, herderite occurs, not in crystals but in a radial fibrous form yielding botryoidal or spheroidal aggregates which are quite new to the species. It was first noted as tiny colorless spheres attached to the tips of albite crystals of acicular habit. These have exactly the translucency and gray color of chalcedony. Later it was found in considerable abundance lining small cavities with a botryoidal coating. Similar fibrous masses coat the beryllonite crystals and form walls dividing the interior of hollow pseudomorphs of that mineral. It is evidently here the product of alteration of beryllonite.

Its fibrous form makes the determination of the optical characters very difficult. Mr. Berman obtained the following data which may be compared to those given in Larsen's Tables or in Dana, System, 761, 1892.

Biaxial negative. 2V large. Axial plane across the elongation, therefore $\gamma=b$
 $\alpha=1.604$ $\beta=1.616$ $\gamma=1.627$

Analysis by Dr. Shannon of a carefully purified sample with specific gravity 2.851, yielded the following results.

	PERCENTAGES	MOLECULAR RATIOS
CaO	32.24	.577
MnO	0.16	.002
MgO	0.76	.019
BeO	16.50	.657
P ₂ O ₅	39.74	.280
H ₂ O	7.97	.442
F	0.87	.046
Al ₂ O ₃	0.50	
CO ₂	none	
Cl	none	
Insoluble	2.02	
	100.76	

The molecular ratio derived from this analysis yields the formula $\text{Ca}(\text{OH})_2\text{Be PO}_4$. This differs from typical hydroherderite in having two molecules of hydroxyl instead of one. The abnormally high content of water is, however, believed to be related to the fibrous form of the mineral, a form favorable to the adsorption of water in many minerals. It is deemed better to accept this explanation rather than seek to establish the mineral as a new species.

EOSPHORITE. Eosphorite, a hydrous manganese aluminum phosphate was first found at Branchville, Connecticut,⁴ and has been found in Maine at Poland, Buckfield and Mount Mica,⁵ always in very small amount. At Newry it is, except for lithiophilite, the most abundant phosphate found. It is always in free crystals implanted on quartz in open cavities or forming fan-shaped groups on albite. The crystals are of simple form, showing the unit pyramid and the two pinacoids $a(100)$ and $b(010)$. They show prismatic development with an almost square cross section. In color they vary from opaque blackish brown to transparent hair brown. The optical characters, determined by Mr. Berman are as follows:

Biaxial negative $2V$ 50° about, $\rho < \nu$ easily perceptible.

$\alpha = b = 1.638$, colorless.

$\beta = a = 1.660$, light yellow.

$\gamma = c = 1.667$, brown.

⁴ Brush and Dana, *Am. J. Sc.*, 16, 35, 1878.

⁵ Landes, K. K. *Am. Mineral.*, 10, 386, 1925.

Material for analysis was obtained by hand picking and crushing the crystals which were then purified in a heavy solution. The specific gravity is 3.067.

The analysis by Dr. Shannon is given in the following table.

	PERCENTAGES	MOLECULAR RATIOS
Al ₂ O ₃	20.51	.201
Fe ₂ O ₃	0.56	.003
MnO	27.65	.390
FeO	3.74	.052
MgO	0.36	.009
CaO	0.84	.015
BeO	0.27	.011
P ₂ O ₅	30.38	.214
H ₂ O	15.59	.866
F	0.18	.009
Insoluble	0.45	
	<hr/> 100.53	

The molecular ratio yields with exactness the usual formula of eosphorite, $2\text{MnO} \cdot \text{Al}_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot 4\text{H}_2\text{O}$. In this occurrence of the mineral the amount of iron replacing manganese (childrenite molecule) is very small, the only analysis showing less iron being that of eosphorite from Buckfield.

NEWBERYITE AND OTHER PHOSPHATES FROM
ASCENSION ISLAND

GRAGG RICHARDS

On the small volcanic island of Ascension, situated in the South Atlantic, latitude $7^{\circ}57'$ south, longitude $14^{\circ}28'$ west of Greenwich, Daly¹ found that "thin deposits of phosphate, on the basaltic flows, occur at many places." Professor Daly kindly placed all of the limited amount of his collections of such material, together with his notes on its occurrence, at the disposal of the writer. Acknowledgement is due to Professor Daly for this kindness and to Professor E. S. Larsen for advice and assistance during this study.

A specimen from the roof of a pressure-dome cavern of a young basaltic flow, running north from the vent 1 km. NNW of 1460-foot Sisters Peak, consists of a fragment of dark colored lava, with the outer surface covered by a botryoidal layer of white to light brown material 5-10 mm. in thickness. A thin section, cut across this crust, shows an outer layer of white, crystalline material, in places with a radial structure, which has an index of refraction lower than balsam. Next beneath this is a layer of yellowish or light brown material, which is amorphous and has an index higher than balsam. Between this and the basalt is a lighter colored, crystalline material of nearly the same index as the overlying amorphous layer. All three layers are not everywhere present on the surface of the specimen, the outer white layer being, by far, the more plentiful and continuous. The basalt is made up of dark glass carrying small laths of feldspar. Toward the crust-covered surface it is somewhat altered and lighter colored.

Practically the pure mineral from the outer layer was readily obtained and, on examination by the immersion method, it was found to have the following properties which identify it with newberyite $2\text{MgO} \cdot \text{P}_2\text{O}_5 \cdot 7\text{H}_2\text{O}$. The crystal form was not well enough developed to determine the optical orientation.

¹ Daly, R. A. The Geology of Ascension Island, *Proc. Am. Acad. Arts & Sciences*, vol. 60, 10, 1925.

	Newberyite, Ascension	Newberyite ²
	biaxial, positive	biaxial, positive
α	1.517 ± 0.003	1.514
β	1.520 ± 0.003	1.518
γ	1.531 ± 0.003	1.533
2V	35° (measured)	45°
Dispersion	$\rho < \nu$ perceptible	$\rho < \nu$
Color	white	white
Specific Gravity	2.30	2.10

The layer of brownish amorphous material is exposed, in places, in the form of small, rounded knobs (3–5 mm.) and is there nearly free from its associates. It corresponds closely to collophanite $3\text{CaO} \cdot \text{P}_2\text{O}_5 \cdot \text{H}_2\text{O}$.

	Collophanite, Ascension	Collophanite ³
	Isotropic	Isotropic
n	1.58–1.59	1.569, 1.61 \pm
	amorphous	amorphous
	conchoidal fracture	
Color	mottled	white, etc.
Specific Gravity	> 2.40 < 2.75	2.7 \pm

The inner layer is the most irregular and least abundant. While mainly in fine aggregates, irregular grains, showing no crystal form, but large enough for study under the microscope, are of not infrequent occurrence. These show the following properties:

² Larsen, E. S. THE MICROSCOPIC DETERMINATION OF THE NON-OPAQUE MINERALS; *U. S. Geol. Surv. Bull.* 679, p. 209, 1921.

³ *Loc. cit.*, pp. 174, 175.

Biaxial, distinctly positive	
α	1.590 ± 0.003
β	1.602 ± 0.003
γ	1.617 ± 0.003
2V	nearly 90° (estimated from several sections normal to an optic axis).
Color	slightly reddish.
Specific Gravity	$2.8 \pm$

These properties correspond most nearly to martinite $5\text{CaO} \cdot 2\text{P}_2\text{O}_5 \cdot 1\frac{1}{2}\text{H}_2\text{O}$.

Martinite ⁴	
β	1.606
B	0.02
2V	medium large
Color	colorless
Specific Gravity	2.89

Some fragments of this material seem to show outlines of feldspar laths in a parallel position, suggesting that the material has replaced the glass of the basalt. A small amount of the material, shown by the microscope to contain a few per cent. each of basaltic glass and colophonite, was obtained for chemical analysis by removing particles of basalt with the electro-magnet and by floating off the minerals of the two outer crusts by the use of heavy solutions with a gravity of 2.75 or less. The analysis corresponds fairly well to the composition $5\text{CaO} \cdot 2\text{P}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$ or with the same ratio of CaO to P_2O_5 as those assigned to martinite but with double the amount of H_2O . The optical properties are so near those of martinite as to identify the mineral as martinite.

⁴ *Loc. cit.*, pp. 105,216.

	Analysis (1)	Molecular Ratios	5CaO · 2P ₂ O ₅ · 3H ₂ O	Martinite, Curacao (2)
SiO ₂	3.76	.0626		
FeO	0.62	.0086		
MnO	0.39	.0055		
MgO	0.21	.0052		
CaO	40.50	.7219	.7728 5 × .1546	45.34
Na ₂ O	1.34	.0216		
K ₂ O	0.94	.0100		
H ₂ O+	7.39	.4106		
H ₂ O—	0.83	.0461	.4567 3 × .1522	8.73
P ₂ O ₅	44.19	.3110	2 × .1555	45.93

100.17

(1) by Mrs. S. Parker, Zurich.

(2) Kloos, quoted from Dana, p. 830.

It is noteworthy that the outer crust is high in magnesia while the inner crust is low in magnesia and high in lime though both are apparently derived from the underlying basalt.

Material collected on the path to Gill's observatory, 500 meters from shore at Mars Bay, SW. corner of the island, consists of stalactitic crusts on lava and finer loose material and dust from hollows on the lava-flow. Some of the stalactites are largely of the white mineral already identified as newberyite but also contain a few small but well formed prisms which show parallel extinction, with n along the prism = $1.510 \pm$ and across $n = 1.702 \pm$. An occasional stalactite carried a few comparatively large white grains with the following properties: uniaxial, negative; $\epsilon = 1.485 \pm 0.003$, $\omega = 1.520 \pm 0.003$. This mineral was readily soluble in water; the solution gave a distinct test for sulphate; tests for the bases were negative, none being made for the alkalis. On allowing the solution to evaporate to dryness, none of this mineral was found but, instead, a few sheaves of colorless, prismatic plates with the plane of the optic axes normal to the length, sections nearly normal to an optic axis being rather frequent. The following properties were determined: biaxial, positive; $\alpha = 1.568 \pm 0.003$, $\beta = 1.590 \pm 0.003$, $\gamma = 1.624 \pm 0.003$; $2V = 60^\circ$ (estimated from sections nearly normal to an optic axis or to the acute bisectrix); dispersion $\rho > \nu$ perceptible.

Of the loose material and dust, grains larger than 40 mesh were nearly all of the amorphous material, already identified as collo-

phanite. The fines through 40 mesh, besides collophanite, also included fine aggregates of newberyite, halite, grains of basalt, and lath-shaped crystals and fragments of a feldspar slightly more sodic than normal labradorite.

The rather plentiful amounts of volcanic glass and of labradorite laths and fragments, in the loose material, may either have fallen as volcanic ash or be a product of disintegration of the lava flow. The comparatively unfractured condition of many of the feldspar laths and their freedom from adhering glass seem to indicate some disintegration either of the lava in place or of small lapilli.

SELIGMANNITE FROM BINGHAM, UTAH

CHARLES PALACHE

Seligmannite, a mineral first described and named by Baumhauer¹ and later analyzed by Prior² and more fully characterized by Solly³ is the arsenical equivalent of bournonite, $\text{Cu}_2\text{S} \cdot 2\text{PbS} \cdot \text{As}_2\text{S}_3$. Hitherto it has been known only from the original locality of the Binnenthal where it has been found in but few examples. The interesting discovery that this rare mineral occurs at Bingham is due to Mr. Lazard Cahn, who identified the mineral and placed the sole specimen in the Holden Collection of Harvard College, giving to the writer the privilege of describing it.

The specimen consists of a small mass of granular pyrite containing two cavities whose walls of crystallized pyrite are coated in turn with sphalerite and splendid tetrahedral crystals of tennantite. Last to form in the cavity are the seligmannite crystals of which there are some twenty-five, the largest not more than 3 mm. in greatest diameter. The crystals are black with a brilliant black fracture and no certain indication of cleavage. The faces of most of the crystals are dull though smooth. A few, however, show excellent, bright faces and six were measured with concordant results. The habit is variable but generally tabular parallel to the base. Most of the crystals seem to be simple twins on $m(110)$. Sometimes the members of the twin are of equal size. More often one is dominant and the twinning may be concealed until revealed by measurement and plotting of the position-angles. The figure shows a typical untwinned crystal.

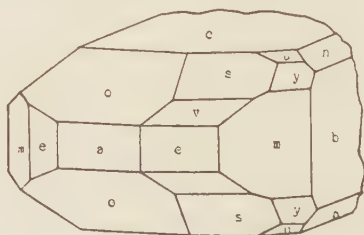


Fig. 1. Seligmannite. Drawing of a crystal showing the forms $c(001)$, $b(010)$, $a(100)$, $e(210)$, $m(110)$, $n(011)$, $v(211)$, $y(111)$, $s(212)$ and $u(112)$.

¹ Baumhauer, H., *Sitz.-ber. Akad. Wiss. Berlin*, 1901, p. 110; 1902, p. 611.

² Prior, G. T., *Mineralog. Mag.*, **XV**, 385, 1908.

³ Solly, R. H., *Mineralog. Mag.*, **XIII**, 336, 1903; **XIV**, 186, 1905; **XVI**, 282, 1912.

As no table of the position-angles of seligmannite has been published, the values of these angles calculated from the axes of Solly are presented in TABLE I. The crystals from Bingham gave angles agreeing in general very well with these. The best readings from 24 faces of the four forms (110), (111), (121) and (211) were employed for calculation of the axes. The results, compared with the axes of seligmannite established by Solly and with those of bournonite, are as follows:

	SELIGMANNITE BINNENTHAL SOLLY	SELIGMANNITE BINGHAM	BOURNONITE
$a:b:c$	0.9233:1:0.8734	0.9217:1:0.8718	0.9380:1:0.8969
p_0	0.9459	0.9469	0.9562
q_0	0.8734	0.8718	0.8969

The forms found on each of the six crystals measured are shown in TABLE II.

It will be noted that the pinacoids $c(001)$ and $a(100)$ are practically always present as are the prisms $e(210)$, $m(110)$ and $i(130)$; the orthodome $o(101)$ and the pyramids $v(211)$, $y(111)$, and $s(212)$.

The forms described as new are for the most part weak faces but the signals reflected by them were as good as those from many of the established forms. The data on which they rest are as follows:

	MEASURED		CALCULATED	
	ϕ	ρ	ϕ	ρ
$\Gamma(830)$	70°58'	90°00'	70°54'	90°00'
$\Lambda(430)$	56 43	90 00	55 18	90 00
$\Xi(430)$	38 36	90 00	39 05	90 00
	38 04	90 00		
$\psi(122)$	27 29	45 17	28 26	44 48
$\sigma(232)$	35 44	58 22	35 50	58 15
	36 30	59 00		
$v(8.11.3)$	38 43	76 10	38 14	76 13

In order to confirm the nature of these crystals as seligmannite, tests were made for arsenic. A crystal heated in the open tube gave a typical arsenic sublimate and the odor of arsenic oxide. Microchemical tests gave a decisive reaction for arsenic and failed to reveal even a trace of antimony. I am indebted to Dr. Short and Mr. Berman for making these tests. Material is lacking for a quantitative analysis without sacrificing the whole specimen which under the circumstances seemed unnecessary.

I. ANGLE TABLE OF SELIGMANNITE.

 $a:b:c=.9233:1:.8734$ (Solly) $p_0=.9459$ $q_0=.8734$

			ϕ	ρ			ϕ	ρ
c	0	001	0° 00'	0°00'	D	$\frac{3}{2}1$	322	58 23
b	0 ∞	010	0 00	90 00	v	21	211	65 13
a	$\infty 0$	100	90 00	90 00	y	1	111	47 17
E	6 ∞	610	81 15	90 00	M	$\frac{2}{3}1$	233	35 50
q	5 ∞	510	79 32	90 00	Ψ	$\frac{1}{2}1$	122	28 26
A	4 ∞	410	77 00	90 00	O	$1\frac{1}{3}$	313	72 53
η	3 ∞	310	72 53	90 00	s	$1\frac{1}{2}$	212	65 13
Γ	$\frac{8}{3}\infty$	830	70 54	90 00	N	$1\frac{2}{3}$	323	58 23
e	2 ∞	210	65 13	90 00	σ	$1\frac{3}{2}$	232	35 50
l	$\frac{3}{2}\infty$	320	58 23	90 00	ω	1 2	121	28 26
Λ	$\frac{4}{3}\infty$	430	55 18	90 00	L	1 3	131	19 51
k	$\frac{5}{4}\infty$	540	53 33	90 00	K	1 6	161	10 14
m	∞	110	47 17	90 00	β	1 8	181	7 43
Ψ	$\infty\frac{5}{4}$	450	40 55	90 00	\S	4	441	47 17
Ξ	$\infty\frac{4}{3}$	340	39 05	90 00	\S	3	331	47 17
f	$\infty 2$	120	28 26	90 00	u	$\frac{1}{2}$	112	47 17
i	$\infty 3$	130	19 51	90 00	ϕ	$\frac{1}{3}$	113	47 17
Φ	$\infty 4$	140	15 09	90 00	\S	$\frac{2}{3}$	229	47 17
α	$\infty 6$	160	10 14	90 00	Π	$\frac{1}{2}\frac{3}{2}$	132	19 51
\ominus	$\infty 8$	180	7 42	90 00	τ	$\frac{1}{2}\frac{5}{2}$	1.10.2	6 11
κ	$0\frac{1}{3}$	013	0 00	16 14	Y	$\frac{3}{2}\frac{1}{2}$	312	72 53
g	$0\frac{2}{5}$	025	0 00	19 15	X	$\frac{7}{3}\frac{1}{2}$	14.3.6	78 48
n	01	011	0 00	41 08	V	$6\frac{1}{2}$	12.1.2	85 36
z	02	021	0 00	60 12	ϵ	$\frac{2}{3}\frac{1}{3}$	213	65 13
Σ	03	031	0 00	69 07	U	$\frac{4}{3}\frac{1}{3}$	413	77 00
F	06	061	0 00	79 12	T	$2\frac{1}{3}$	613	81 15
B	07	071	0 00	80 42	S	$\frac{7}{3}\frac{1}{3}$	713	82 29
Δ	$\frac{1}{5}0$	105	90 00	10 43	δ	$\frac{7}{2}\frac{5}{2}\frac{7}{2}$	752	56 36
l	$\frac{1}{4}0$	104	90 00	13 18	π	$\frac{9}{2}\frac{7}{2}$	972	54 19
ϵ	$\frac{1}{3}0$	103	90 00	17 30	ν	$\frac{8}{3}\frac{1}{3}$	8.11.3	38 14
x	$\frac{1}{3}0$	102	90 00	25 18	ξ	3 4	341	39 05
h	$\frac{2}{3}0$	203	90 00	32 14	ζ	4 5	451	40 55
o	10	101	90 00	43 24	μ	5 6	561	42 04
I	20	201	90 00	62 08	λ	7 8	781	43 28
H	$\frac{7}{3}0$	703	90 00	65 38	W	4 3	431	55 18
G	60	601	90 00	80 00	γ	5 4	541	53 33
Ω	14.1	14.1.1.	86°13'	85°41'	J	6 5	651	52 25
T	$\frac{1}{2}1$	11.2.2.	80 28	79 16	Z	2 6	261	19 51
C	31	311	72 53	71 23				79 49
P	61	611	81 15	80 07				
Q	$\frac{7}{3}1$	733	68 25	67 09				
R	$\frac{5}{3}1$	533	61 01	60 59				

TABLE II. COMBINATIONS OF FORMS, SELIGMANNITE, BINGHAM

	<i>c</i>	<i>b</i>	<i>a</i>	<i>q</i>	A	Γ	<i>e</i>	<i>l</i>	Λ	<i>m</i>	Ξ	<i>f</i>	<i>i</i>	Φ	Θ	κ	<i>n</i>	<i>z</i>	Σ	<i>o</i>	<i>v</i>	<i>y</i>	Ψ	<i>s</i>	σ	ρ	<i>u</i>	φ	<i>v</i>	<i>W</i>
1.	<i>x</i>		<i>x</i>		<i>x</i>		<i>x</i>	<i>x</i>		<i>x</i>		<i>x</i>							<i>x</i>	<i>x</i>	<i>x</i>		<i>x</i>					<i>x</i>		<i>x</i>
2.		<i>x</i>	<i>x</i>		<i>x</i>		<i>x</i>	<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>			<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>			
3.	<i>x</i>	<i>x</i>	<i>x</i>				<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>							<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>					<i>x</i>			
4.	<i>x</i>	<i>x</i>	<i>x</i>				<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>						<i>x</i>			<i>x</i>	<i>x</i>	<i>x</i>		<i>x</i>			<i>x</i>			
5.	<i>x</i>		<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>		<i>x</i>	<i>x</i>		<i>x</i>		<i>x</i>				<i>x</i>	<i>x</i>	<i>x</i>			<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>
6.	<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>		<i>x</i>		<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>			<i>x</i>	<i>x</i>	<i>x</i>		<i>x</i>		<i>x</i>	<i>x</i>			

A NEW METEORITE FROM WASHINGTON COUNTY,
COLORADO

CHARLES PALACHE AND EARL V. SHANNON

The meteorite here described was acquired in February, 1927, by the Harvard Mineralogical Museum through Ward's Natural Science Establishment. The rather meager information regarding its discovery was obtained by R. D. George, State Geologist of Colorado from the finder, Eugene King, and was placed at our disposition for publication.

As the meteorite was not seen to fall no exact date can be given for it; but Mr. King thinks that it probably fell in 1916. It was found in a wheat field buried about 12 inches deep. The finder thought to see evidence of heat in the soil in which the iron was imbedded sufficient to convince him that it had fallen but recently. As it is an iron meteorite and shows almost no sign of rusting, his conclusion is probably correct.

The location of the fall was given as NE $\frac{1}{4}$, S 23, T 4S, R 52W, Washington County, Colorado. This point is approximately in latitude 39°42' N., longitude 103°10' W. Mr. George writes that this locality is about six miles west and a little south of Arickaree Postoffice but that these country postoffices are migratory in character, this one having changed its location three times since 1913. The nearest town is Flagler, a station of the Union Pacific Railway which is 28 miles south and about three miles east of the point of fall. Under the circumstances it seems best to designate the meteorite as the Washington County, Colorado fall.

The meteorite consists of a single very symmetrical disk of iron, slightly ellipsoidal, with major dimensions of 15 and 20 cm. and a maximum thickness of 6 cm. It weighs 5750 grams or about 12½ pounds. As shown in the photographs one surface is slightly conical with imperfectly radial flutings. This was probably the "breast" or front surface of the iron in its flight. The other surface is much smoother, and the edge of the disk so beveled, smooth and even as to suggest its having been cast in a mold. As it was impossible to slice the iron without marring its symmetry, an area in the center of the smoother face was evened off in a planing



FIG. 1.

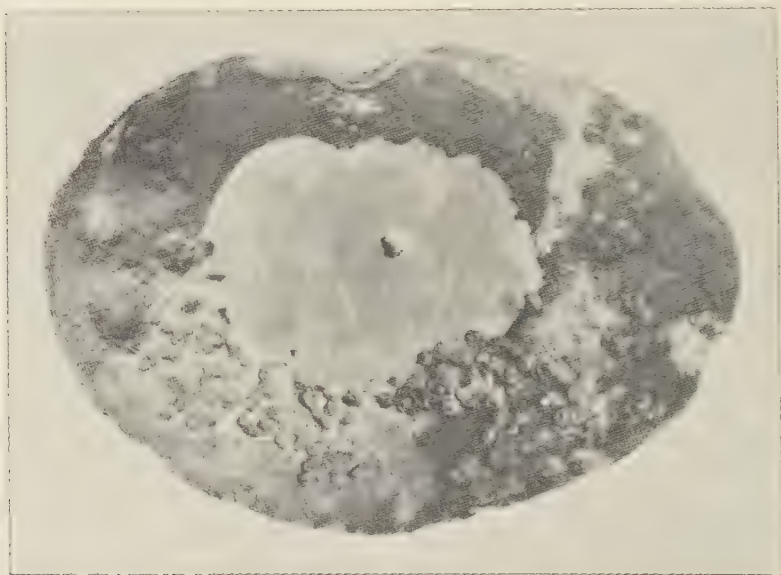


FIG. 2.

EXPLANATION OF PLATE XIV

Fig. 1. Meteorite, Washington County, Colorado. Upper side.

Fig. 2. The same, lower side. The flat area in the center is a planed surface.

Photographs by U. S. National Museum.

machine and the surface thus obtained was polished and etched. The iron was soft and worked easily under the tools. No nodules or irregularities of any sort appeared on the polished surface and etching produced a matte surface without structural features. It is therefore to be classified as an ataxite, A.

The analysis was made according to the following procedure. The sample as received consisted of approximately 117 grams of coarse dry shavings from a planing machine. No dust was present in the jar containing the sample. The form of the sample was convenient although it was necessary to assume that the sample thus prepared was homogeneous and representative of the iron as a whole. This presumes that no brittle constituents such as troilite or schreibersite were broken out and lost.

One sample of 10 grams was dissolved in dilute nitric acid, made up to 300 cc. with water and divided into three aliquot portions which were used for the determination of manganese, sulphur, and phosphorus.

A second sample of 10 grams was dissolved in aqua regia and used for the determination of iron, nickel and cobalt.

The balance of the sample, 97 grams, was dissolved in hydrochloric acid and nitro-hydrochloric acid and used for the determination of copper and platinum. The insoluble material from all three portions was weighed. It consisted of dust and a little graphite. No chromium reaction could be obtained from it. The analysis gave the following results:

Analysis of Washington County, Col. Iron. E. V. Shannon, analyst.

	PERCENTAGES
Insoluble	0.004
Iron	90.078
Nickel	9.342
Cobalt	0.548
Copper	0.010
Manganese	trace
Platinum	trace
Chromium	absent
Phosphorus	0.298
Sulphur	0.003
	<hr/>
	100.283

The analysis proceeded smoothly, many of the determinations being checked carefully by different methods, and confidence is felt in the accuracy of the figures.

There seems to be little to add to this statement. It is evidently a moderately nickel-rich ataxite. The presence of copper and platinum is noteworthy. The low content of phosphorus and sulphur agrees with the physical evidence that troilite and schreibersite are practically absent.

